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Decarbonizing household heating: Reviewing demographics, geography and low-carbon practices and preferences in five European countries

Benjamin K. Sovacool [a,b,*], Luisa F. Cabeza [c], Anna Laura Pisello [d], Andrea Fronzetti Colladon [d], Hatef Madani Larijani [e], Belal Dawoud [f], Mari Martiskainen [a]

[a] Science Policy Research Unit (SPRU), University of Sussex Business School, University of Sussex, United Kingdom
[b] Center for Energy Technologies, Department of Business Development and Technology, Aarhus University, Denmark
[c] GREiA Research Group, University of Lleida, Pere de Cabrera S/n, 25001, Lleida, Spain
[d] Department of Engineering, University of Perugia, Via G. Duranti 93, 06125, Perugia, Italy
[e] KTH Royal Institute of Technology, Sweden
[f] Ostbayerische Technische Hochschule (OTH Regensburg), Faculty of Mechanical Engineering, Galgenberg Street 30, 93053, Regensburg, Germany

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ABSTRACT

What commonalities are there in sustainable or unsustainable heating practices in five high-income, high-emitting western European countries? What preferences do a nationally representative sample of the public in these countries hold towards low-carbon options? It is imperative that climate policy researchers and practitioners grapple with the difficulty of decarbonizing heat, which remains the largest single end-use service worldwide and which accounts about half of total final energy consumption. Based on a comparative assessment of five representative national surveys in Germany (N = 2009), Italy (N = 2039), Spain (N = 2038), Sweden (N = 2023), and the United Kingdom (N = 2000), this study explores the demographics and geography of household heat decarbonisation in Europe. By analyzing our country level data as well as our combined sample of 10,109 respondents, it investigates how people conceive of the purposes of low-carbon heat, their preferences for particular forms of heat supply, and their (at times odd) practices of heat consumption and temperature settings. Grounded in its original data, the study organizes its findings inductively across the five themes of literacy (heating knowledge, awareness and control), sustainability (heating practices, dynamics and conflicts), temperature (heating satisfaction and preferences), desirability of change (low-carbon heating priorities, business models and trust), and culture (country and national variation). The study also explores intersections between these dimensions, using multivariate analysis, as well as how preferences differ according to varying types of actors as well as geography and space.

1. Introduction

It is imperative that energy and climate policymakers and researchers grapple with the difficulty of decarbonizing heating and cooling, because the largest single end-use service related to energy remains heating and cooling, accounting for roughly *half* of worldwide total final energy consumption [1] However, the International Energy Agency (IEA) also estimates that only 10% of heat production annually comes from low-carbon or renewable sources. In the European Union (EU), despite all of its progress towards setting ambitious energy and climate goals, 84% of heating and cooling needs are still met by fossil fuels [2]. Heat also remains one of the most significant contributions to European household carbon footprints, far more than from electricity or other household energy services [3].

Despite this almost obvious imperative of decarbonizing household heat, getting households to adopt low carbon forms of space heating and cooling is difficult. Krausmann et al. [4] caution that tackling energy consumption in buildings, especially heat, represents a "key challenge" for meeting and complying with global carbon targets. Hansen [5,6] argues that household heat consumption is so resistant to change because it is embodied in both existing long-lived infrastructures and social practices [5,6]. Other studies emphasize decarbonizing heat as a complex sociotechnical problem that involves a seamless web of infrastructure and building stock, patterns of incumbency and path

* Corresponding author. Science Policy Research Unit (SPRU), University of Sussex, Jubilee Building, Room 367, Falmer, East Sussex, BN1 9SL, UK.
E-mail address: B.Sovacool@sussex.ac.uk (B.K. Sovacool).

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dependence, the sales practices of installers and professional networks, and socioeconomic drivers such as income and poverty [7–9]. These contextual factors make heat perhaps more prone to "path dependence" [10] or "lock-in" [11] than other energy services or sources of supply. The implication from this growing body of evidence is that heating and cooling practices are unsustainable, and locked into staying that way.

In this study, we ask: What commonalities are there in sustainable or unsustainable heating practices in five high-income, high-emitting western European countries? What preferences do a nationally representative sample of the public in these countries hold towards low-carbon options? Aiming for an empirically novel and robust paper, we explore these aspects of heat based on an original large-scale survey in five European countries. Our final sample comprises 10,109 respondents spread across the United Kingdom (UK) (N = 2000), Germany (N = 2009), Italy (N = 2039), Spain (N = 2038), and Sweden (N = 2023). Based on our survey data and results, we tackle many of these dimensions of heat head on, and explore:

- Literacy, including heating knowledge, awareness and perceived or self-reported control (important themes in energy consumption research arising from Refs. [30,31]);
- Sustainability, which includes heating practices, dynamics and conflicts (important themes in Refs. [32–34]);
- Temperature, which includes heating satisfaction and preferences (important themes in Refs. [35–37]);
- Desirability of change, which includes heating priorities, business models and trust (themes in Refs. [38–44]);
- Country and cultural variation, and how our results differ across the five European countries (themes in Refs. [45–51]).

Building on an analysis of these five dimensions, the paper then analyzes intersections among these attributes, actors, and some of the geographic and spatial implications of our research.

The paper proceeds as follows. Given that our contribution is intended to be more empirical than theoretical, and also that we had a copious amount of data to deal with (meaning the paper is "saturated" with findings or at least results), we did not have the space to present a literature review on heat or to posit some sort of conceptual framework on heat. Therefore, Section 2 explains our selection of European countries before summarizing our research design (a survey instrument), data analysis techniques, and limitations. We then introduce our core Results organized thematically around the five issues of literacy, sustainability, temperature, change, and culture in Sections 3-7. We lastly discuss these findings in Section 8 in terms of interconnections, actors, and geography before concluding.

2. Case study selection and research methods

2.1. National case study selection

Our empirical analysis centers on Western Europe, which was connected particularly to our funding scheme (see acknowledgments). However, even though we had to select European countries we nevertheless chose a different mix of countries in terms of location (north and south), energy markets (dominated by gas or renewables) and length of heating season. We ended up with:

- Germany: moderate climate, primarily gas and oil heating, heating season is November to April;
- Italy: mild climate, gas, heating season is December to March;
- Spain: mild climate, gas and electricity, December to February;
- Sweden: cold climate, low-carbon district heating and electrically-driven heat pumps or boilers, winter season is October to April;
- UK: moderate climate, gas, average heating season November to April.

We maintain this offers an authentic range of countries in terms of their geographic location, energy and heating sources, and climatic conditions. Our case study selection also had the benefit of drawing from authors from the project in each of the selected countries, a notable strength.

2.2. Research design and analytical protocol

Our survey instrument focused on heating practices and knowledge and the social acceptance of low-carbon options. It was designed to take 10–15 min to complete, and it consisted of 23 questions across five sections. The first section explored the socioeconomic and demographic attributes of respondents. The second section investigated heating knowledge and awareness. The third section examined heating practices and dynamics. The fourth section analyzed heating satisfaction and preferences. The fifth section studied heating priorities and business models. Most questions used a 4-point or 5-point Likert type option (e.g. 1 = none, 4 = advanced; 1 = strongly disagree, 5 = strongly agree), although a final question was open ended, and asked respondents to discuss qualitative interactions with their heating systems. For these answers, we assigned a respondent number, e.g. R1 or R1004.

The survey was offered in English in the UK, but fully translated by professional language editors into German, Italian, Spanish and Swedish for the other countries, to increase accessibility and completion rates. The survey was implemented online by a market research company, Dynata, using a respondent panel representative of the five European countries (Germany, Italy, Spain, Sweden, and the UK). Dynata scripted an online version of the survey instrument using their proprietary software. Once checked by the research team, Dynata sent unique person-specific links to the survey to individuals in their respondent panel who have agreed previously to take part in survey research in exchange for incentives. The sampling frame consisted of adults in each of the five countries who had to be over the age of at least 18 years old.

A total of 514 respondents were screened out based on quality checks. These quality checks included "flat-liners," those who gave straight-line responses on blocks of questions; "rushers," those who gave incomplete, contradictory or unrealistic responses (e.g., the respondent who claimed to have 99 children); and "speeders," those who had unrealistically fast survey completion times. The final sample comprised 10,109 respondents spread across the UK (N = 2000, Respondents 1 to 2000), Germany (N = 2009, Respondents 2001 to 4010), Italy (N = 2039, Respondents 4008 to 6047), Spain (N = 2038, Respondents 6047 to 8085), and Sweden (N = 2023, Respondents 8086 to 10,109). Because of the quality checks, our final sample includes *complete* response rates, that is each participant answered *every* question.

Fig. 1 shows some of the demographic details of our final sample, which were ensured to be nationally representative for gender, age, income, and region. The survey sample had the added benefit of being very recent, with all respondents completing the questionnaire in 2020, making our results extremely up to date as of the time of publication.

2.3. Data analysis techniques

The survey results were first analyzed descriptively and at times with the help of frequency analyses and single level statistical analyses. However, in order to evaluate possible significant associations among the variables in our study, we started with a correlation analysis. We calculated Person's correlation coefficients and assessed their significant at the 0.05 and 0.01 level, with a two-tailed test. We also used a Mann-Whitney *U* test to examine any significant differences at 0.05 level between one country's responses with all of the other countries. For this, all 4- and 5-point Likert-type answers were recoded into the same order (e.g. lowest number disagree and highest number agree). We also used Benjamini -Hochberg Procedure as a post-hoc test to control for false positives [52].

A second part of our analysis, mentioned mostly in the Discussion

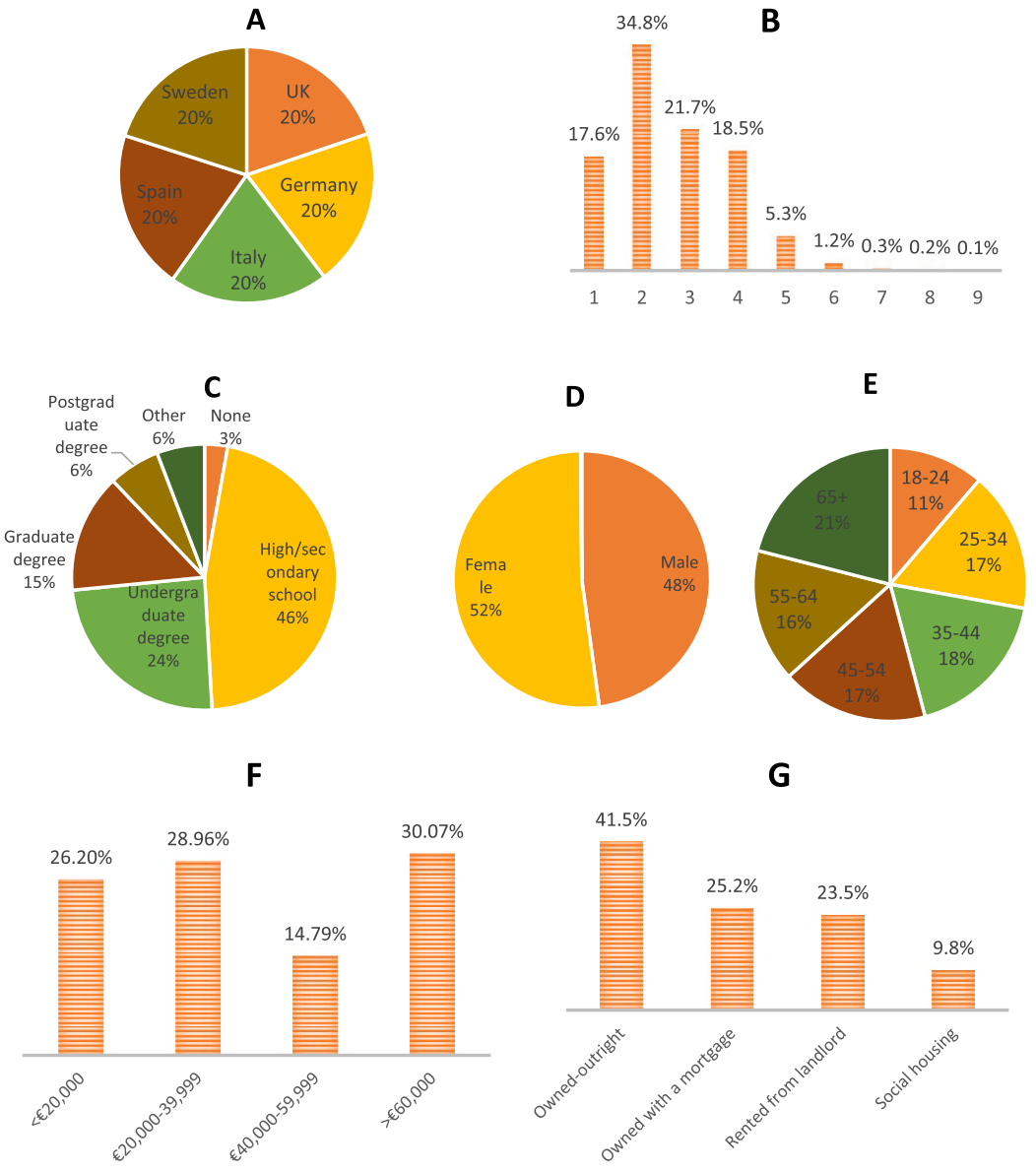

Fig. 1. Demographic details of heating and cooling survey respondents in five European countries. Panel A refers to the percentage of respondents from each of the five countries. Panel B is the average household size of participants. C is self-reported level of education. D is gender. F is annual total household income. E is age. G is home ownership.

section, consisted in testing if significant differences – in literacy, willingness to change and energy-related behaviors – could be observed depending on the country of respondents, or on their house ownership. To this aim, we carried out an analysis of variance (ANOVA) to see if, overall, group means were significantly different. We completed this analysis with post-hoc tests, to compare groups in pairs and identify which particular differences were significant. One assumption of classical One-Way ANOVA is homogeneity of variance, which means that the variance among the groups should be approximately equal. However, this assumption was violated in our sample, as confirmed by the Levene's tests for homogeneity of variance that we carried out. Accordingly, in order to perform a robust analysis, we replaced classic ANOVA with the Welch test for the equality of group means, which does not require variance homogeneity. Similarly, we performed a Games-Howell post hoc analysis [12] to carry out robust pairwise multiple comparisons. Although similar to Tukey's test, the Games-Howell test does not assume equal variances and sample sizes.

Lastly, we looked at the interclass correlation coefficients (ICC) that we calculated after building empty multilevel regression models [13,14] – which just included the constant term with fixed effects depending on the country of respondents. We did this analysis in order to see which proportion of the variance of each dependent variable was attributable to the country of respondents (and which was the residual part).

2.4. Limitations

Proceeding on this path, our aim is for an empirically robust and novel paper, one that the methods literature describes as "new applications of existing methods … (e.g. to different regions, contexts or research questions), as well as through analysis of new types of evidence or data" [15] pg, 14]. This means most of our analysis below is grounded not in theories or broader sets of literature but the data itself, similar to the "grounded theory" approached used in some disciplines such as ethnography, geography, and sociology. There also wasn't sufficient

space to test theoretical propositions in the survey alongside all of our practical questions. Even though this type of paper has novelty for its large empirical dataset, we nonetheless hope that it can be used to help inform others seeking to develop theory or also calibrate energy models, predict energy-related consumer behaviors, and other research designs. Moreover, rather than split this paper into a number of derivative papers that "slice" its results into separate outputs, our intent was to place everything in a grand, single "big" paper. This makes it long but also (we hope) more coherent and complete.

Although we believe that the paper has a high degree of validity and rigor, our research design does have some notable limitations. First, while our five national country samples are representative in terms of gender, age, income, and location, we cannot guarantee representativeness beyond these categories, e.g. household size, education or home ownership. Second, because our data are representative, these include many respondents who may have little awareness or knowledge about heat, and many who may not have actually adopted low-carbon heating technologies. Third, we treat responses as stable and fixed, soliciting them at a single point in time, whereas in reality they are flexible, fluid, and co-constructed over time. Fourth, due to space constraints, we could not deeply analyze all 23 survey questions in this paper or present all results in their entirety.

3. Literacy: heating knowledge, awareness and control

This section is our first to present our results; it does so by focusing on the heating knowledge or energy literacy aspects of the survey, including their attention to and awareness of heat in the household. This also included how heat is perceived to be provided, and how households reported they managed heat in the home.

3.1. Knowledge and attention/awareness

As a starting point, respondents were asked "How much would you say you know about how your home and water is heated?" As Fig. 2 reveals, self-rated heating knowledge was generally high, with most respondents indicating they had moderate to advanced heating literacy. Self-described advanced literacy in particular varied by country, with the UK and Italy reporting far higher rates than Sweden or Germany. The level of attention households reported paying to heat also varied considerably, with more than one-quarter of all respondents suggesting they had "none at all" to "not very much." Conversely, those reporting a fair amount to high attention to heat were the largest in Italy (93.5%), followed by the UK (84.7%) and Spain (78.6%). Sweden had by far the lowest prevalence of attention (43.2%) perhaps related to their high incidence of district heating (42.8% of homes in Sweden report being supplied by heat networks or district heating systems). We also see the Swedes having some of the lowest numbers of stated control over their heating systems as a result, which also implies that low-carbon systems do not always go hand-in-hand with perceptions of enhanced personal control.

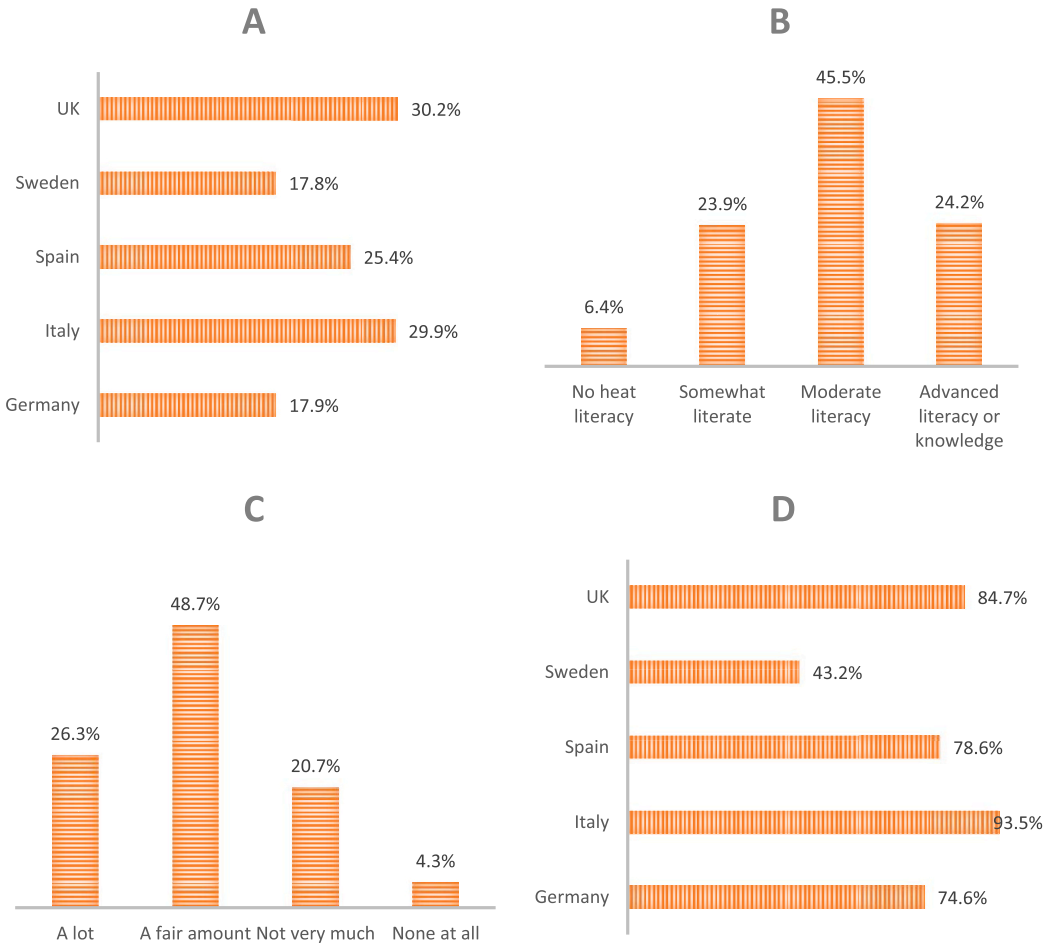

Fig. 2. Heating knowledge, literacy, and awareness of heat self-reported by respondents (N = 10,109). Panel A is self-reported advanced literacy by country. B is self-reported knowledge of heating. C is reported level of attention to heat. D is the percentage of respondents with a high attention to heat. "High attention to heat" refers to respondents who either answered either "a fair amount" or "a lot."

3.2. Current heating

When asked "What is the main way you currently provide heat in your home?" most respondents (almost half) relied exclusively on gas, despite offering the survey in five very different countries, policy environments, and energy markets (see Fig. 3). When looked at by country, and the % heated by fossil fuels (gas, oil), variation was significant with the UK (79.3%) and Italy (69.8%) having a dominance of fossil fuel heating contrasted with Sweden at only 3%. We also asked how homes currently pay for their heat. About half (52.4%) pay the conventional way of purchasing a volume of electricity or gas and paying monthly to quarterly bills. A solid 29.6% of respondents paid for heat via a network or a building manager to guarantee a set temperature. About 18% do not know or selected another type of payment service. As a particularly promising sign for possible decarbonisation potentials, more than 60% of respondents in the UK, Spain and Italy all reported paying for their heat via an individual oil or gas boiler, heat pump, or electricity.

3.3. Control, management and use

Our final aspect of literacy and knowledge explored related to heating control and use. Across the survey population, many homes have limited to no heating controls at all, and only 11.4% reported having advanced or smart heating controls in Fig. 4. The prevalence of no to limited heating control was reported to be highest in Spain (58.4%) and Sweden (56.6%) followed by Italy (50.2%). When asked who uses or controls household heating, most respondents (70.9%) suggested that they themselves did, followed by their partners (34.1%). This personal control was reportedly the highest in the UK (83.1%) followed by Spain (77.4%) and Germany (73.9%). As mentioned above, it was reportedly the lowest in Sweden (47.8%).

Issues of control came up with recurring importance in our open-ended question of the survey as well. R179 (UK) wrote about lack of control leading to emotions and anxiety over heat, noting that:

Once I was not at home and turned the heating off and it turned back on automatically and when I arrived the home was too hot that I thought there was a fire.

R283 (UK) talked about the necessity of easy to use controls, stating that:

I accidently switched off the boiler thinking it was the light switch ……then I rang the company telling them my boiler was not working.

R877 (UK) echoed this concern when they said:

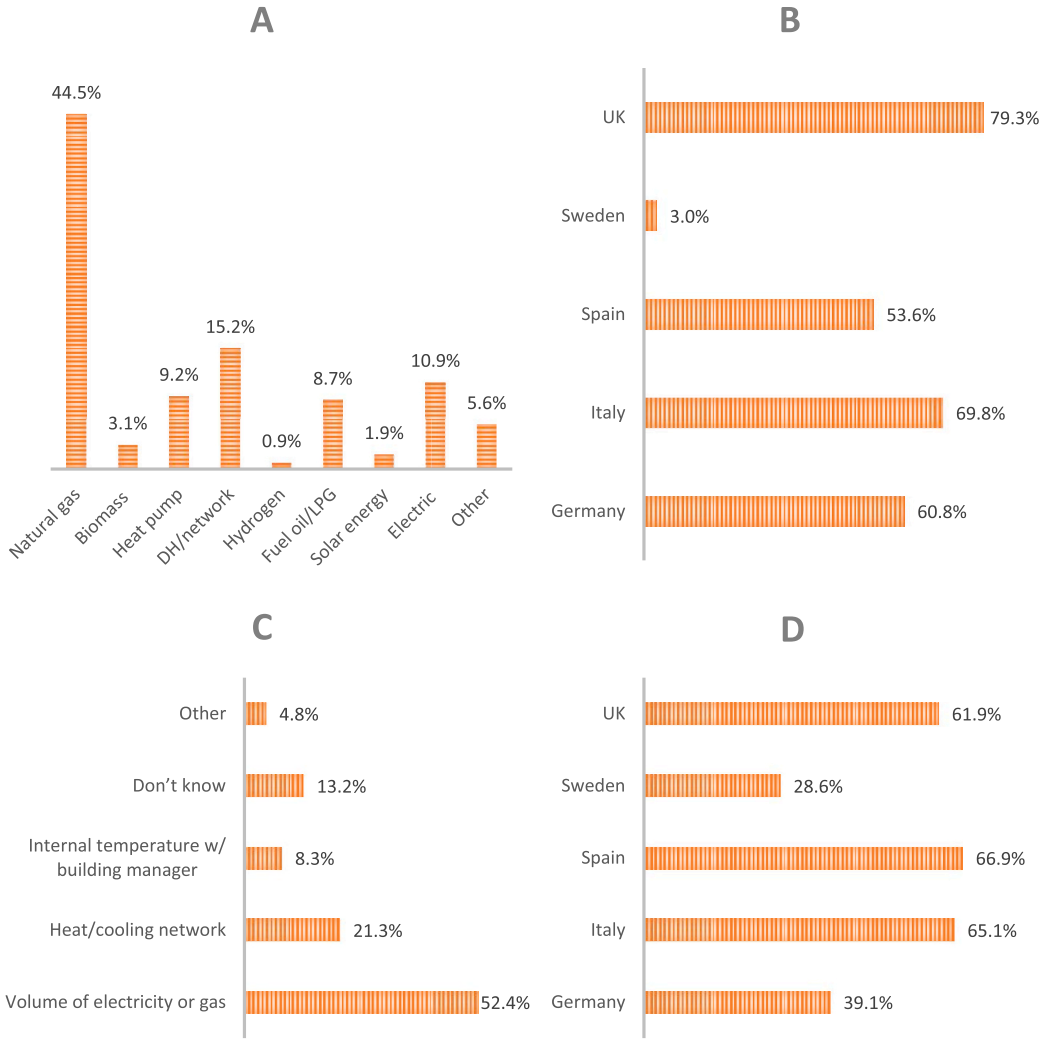

Fig. 3. Current sources of household heat and methods of payment (n = 10,109). Panel A refers to the type of heating system reported by respondents. Panel B the percentage of participants who said they had fossil-fueled heating. C describes how households currently pay for their heat. D refers to those households that pay individually for heat from an electricity network, heat pump, fuel oil, or gas boiler. DH = district heat. "Fossil-fueled heating" refers to gas, fuel oil, and liquefied petroleum gas.

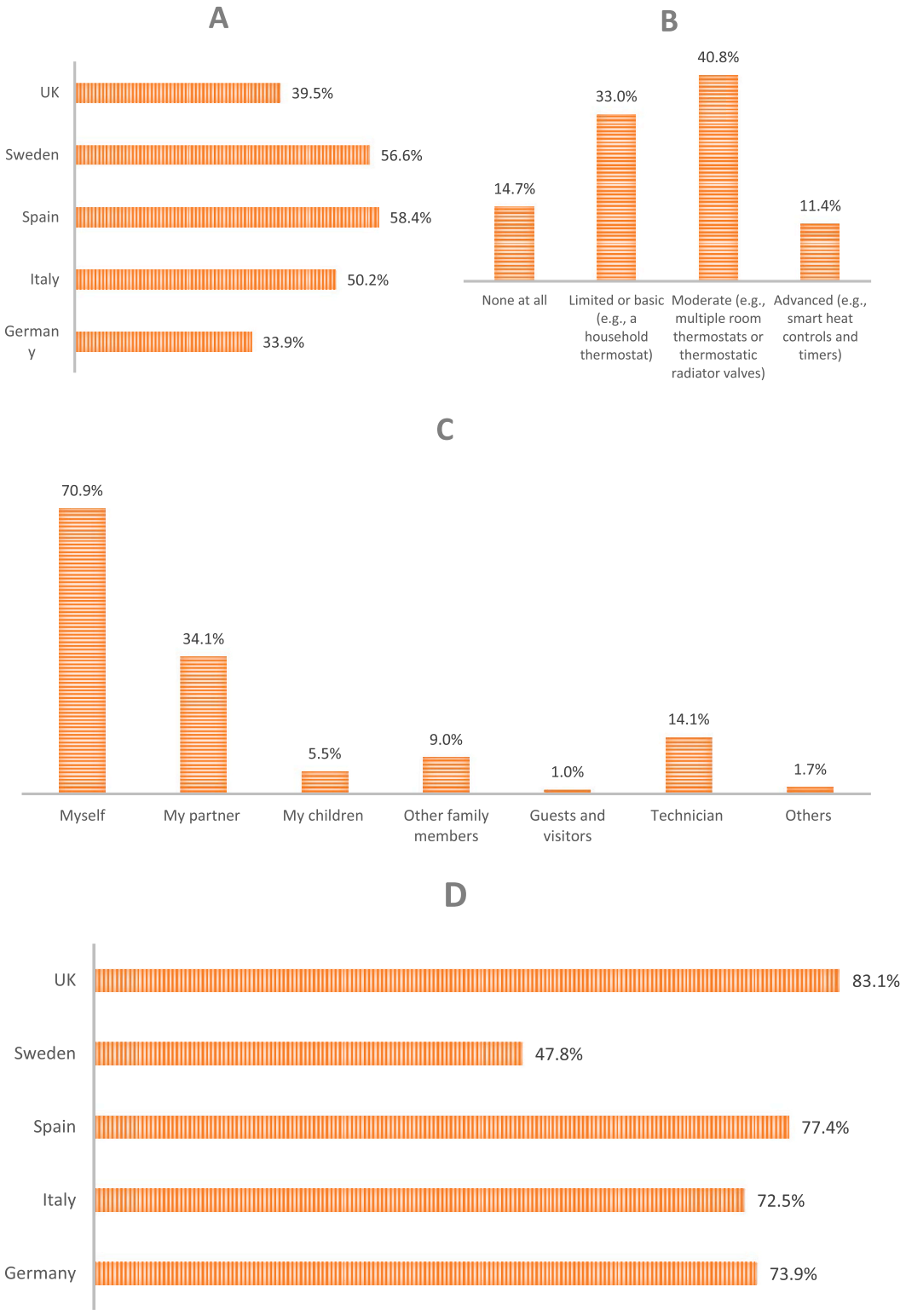

Fig. 4. Current levels of household heating control and patterns of use (n = 10,109). Panel A shows respondents reporting they had no to limited control over heat by country. Panel B levels of control across the entire sample of respondents. Panel C shows who uses or controls household heating. Panel D personal control over hearing by country.

Once my fiancé called our boiler man saying there was some trouble with the heat. Turns out she hadn't turned it on!!

R812 (UK) wrote about how confusing it was to learn to use their new heating system, saying:

We bought new property with heating arrangements already made. They provided a complicated handbook on how to install the system but no advice on how to use it!

R2334 (Germany) seems to have learned an even harsher lesson about control, noting:

When refilling the heating with water, I turned on the wrong tap and I got

an involuntary shower!!

These statements all imply that as important as heating control is, it remains unintuitive for many households and also may serve as evidence that more automated or smart controls can minimize many of these instances of poor or confused control. They also buttress the finding that simplicity and comprehensibility should be an inevitable characteristic of the future smart control systems.

4. Sustainability: heating practices, dynamics and conflicts

In this section, we look more closely at our results over heating practices. This includes how important homes view heat as an energy security or services issue, as well as heating practices, habits and profiles, and how much these connect with the goals of decarbonisation and sustainability (or not), such as opening windows or the numbers of heated rooms. Lastly, this section examines issues of conflict that may emerge over such heating practices and dynamics.

4.1. Importance of heat as an energy service

To begin, Fig. 5 illustrates how our respondents, as a whole, strongly believed heating was the single most important energy service (compared to say lighting, entertainment, refrigeration, etc.). This belief in heat as a critical energy service was the strongest in Germany (61.1%) and Sweden (59.5%). However, it is perhaps striking to non-Northern Europeans that heat is valued as the most important service in almost half of respondents in the milder Mediterranean countries of Italy and Spain.

4.2. Wasteful and unsustainable practices

Our next questions were intended to interpret the extent of possibly wasteful or inefficient heating practices. We asked respondents if it was acceptable to keep the heat on all year round, with more than 17% in Fig. 6 indicating they agreed or strongly agreed. More than 70% of people in the UK, Italy, and Germany also reported opening windows in the middle of winter to let in fresh air. Respondents reported a perceived necessity of heating for a variety of other aspects including heating every room (even if rooms are not in use, 41%), heating for pets (27%), and opening windows in the middle of winter (68%). Similarly, 38% of all respondents agreed or strongly agreed that homes needed to be warm enough to wear shorts or t-shirts in the dead of winter. This belief was the strongest in our two northernmost countries of Sweden (45.3%) and the UK (38.6%), which is slightly surprising, given these countries have the coldest climates (and thus one may expect greater heat awareness or more reasonable expectations).

Indeed, although we never asked about them in the survey itself, the open-ended question did reveal a collection of unanticipated and perhaps just plain weird heating practices mentioned by respondents. R3558 stated a particularly odd notion of what constitutes warm or sufficient heat, saying:

I look for heating that leaves red streaks on my arse [bum or bottom] after warming up, right now it is only the bathroom that can do this for me and I love it.

R6228 said:

I like to put my feet with my socks on the stove and I warm them for a while until I suddenly realize that it smells like burning and I am toasting my socks on the stove so I have to stop.

R9533 personified their heating system as a child, and referred to it as such when out:

In our previous apartment, we had boiler that we called "Baby," for it needed to be guarded and fed. Whenever anyone asked if we had children, we would laugh and say "we always have Baby, baby."

These examples, while rare and hardly representative, surely reveal the complex and non-rational ways that people engage with their heating sources.

4.3. Heating activity or preference conflicts

These sets of questions focused on heating practices and dynamics, especially possible "thermal conflicts" in use and control in the home [16]. Respondents confirmed in Fig. 7 that heating was likely to lead to possible tension or conflict with housemates, couples and partners, landlords and tenants, and children and parents (all roughly one-third). About one-fifth of respondents suggested it was likely to highly likely conflicts between hosts and guests, or neighbors, could also result. Potential conflicts with landlords were reported to be most pronounced in the UK (42.5%), followed by Spain (40.9%) and Sweden (40.5%). Germany, by contrast, seemed to have the best or kindest perceived landlords and property agents within the bunch (only 30.2% of Germans spoke about possible heating conflicts with them), or perhaps the inclusion of heating fees into rental contracts and leases which would minimize possible contact with landlords or heat suppliers.

Landlords came up, in particular, in our open-ended question in the

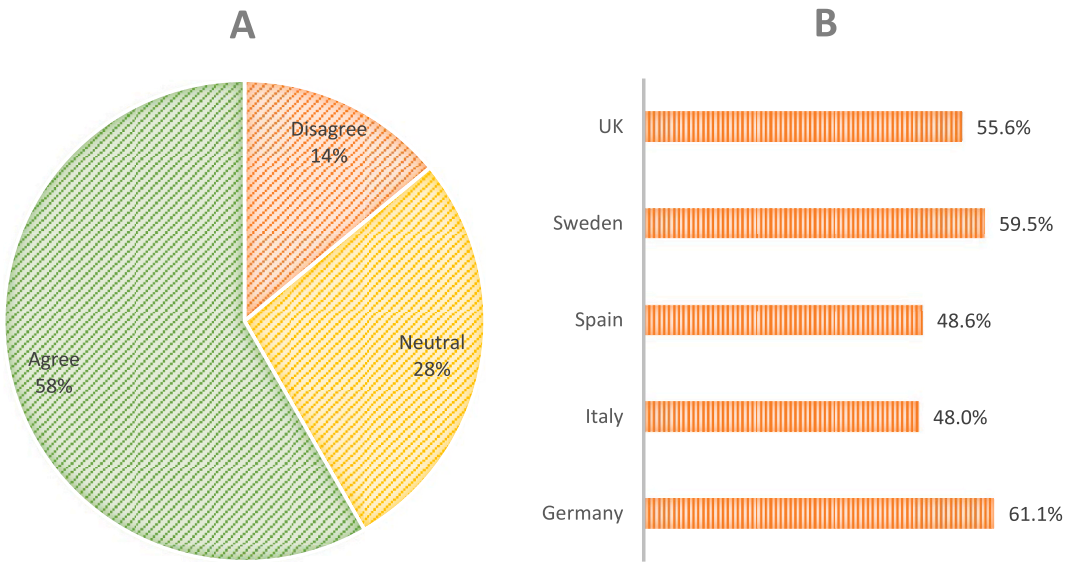

Fig. 5. Survey respondents who agreed that "heating is the most important energy service" (n = 10,109). Panel A shows respondents across the whole sample and Panel B shows them organized by country.

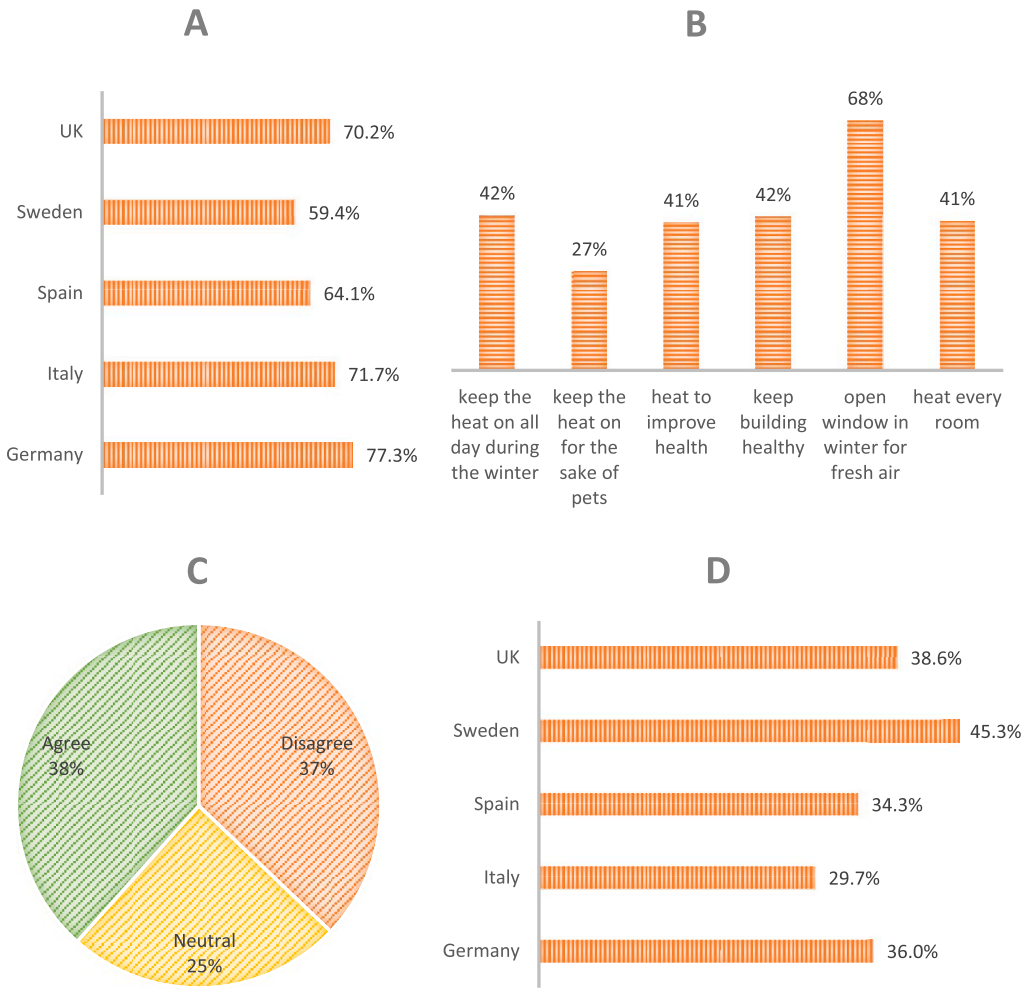

Fig. 6. Household heating dynamics and potentially wasteful practices (n = 10,109). Panel A shows those indicating it's ok to open the windows in the winter for fresh air by country. Panel B shows perceived necessities of heating services across the entire sample. Panel C shows responses to the question that homes should be warm enough for shorts and t-shirts in the winter for the whole sample, Panel D answers by country.

survey. R8191 (Sweden) said that:

My landlord has been taking steps to improve the indoor climate (radon and asbestos). However, he chose to drill large holes at the top of the window so now the windows will definitely mold. It looks like the mafia has been over and shot my house up with a shotgun. It is now so terribly very cold in the apartment that none of my friends want to come and visit anymore.

R8603 (Sweden) mentioned that:

My previous landlord had sometimes forgotten to order oil for the boiler so he came with jars that he filled with. I don't know where from though, maybe his car?

More seriously, two respondents spoke about grave conflicts with landlords with issues pertaining to health and personal security. R9370 (Sweden) stated:

My landlord [name] during the winter of 19/20 had no heat on and refused us accommodation to put the heat on the despite repeated complaints from many tenants. This has led to illness due to the cold (as cold as it is by and large).

R1257 (UK) remarked that:

I have a live-in landlord who insisted that it wasn't cold in the house and my thermometer was out of order. He suggested I get in bed with him so that he could keep me warm!

Nevertheless, while conflicts with landlords were prominently mentioned by respondents, they were not the only possible sources of conflict. Numerous respondents talked about fighting with partners or spouses over heat:

R135 (UK): *Wife turns it up, I turn it down.*

R365 (UK): *My wife is too hot in the summer and so I use an air con and in the winter I use gas heating controlled by Hive. She is warm and I am boiling so I sit in front of a fan.*

R505 (UK): *Myself [sic] and my partner have very different ideas over what is an acceptable temperature for staying warm.*

R539 (UK): *My partner is older so has the heating on often, and high. I'm wandering around in a sarong!*

R1471 (UK): *Just me [sic] and my partner always argue about it. He is permanently sweaty!*

R1679 (UK): *The wife thinks we live in a desert.*

R4522 (Italy): *I lower the valve because I'm hot and my husband comes after me to raise them.*

Others recollected about fighting with their parents or other family members:

R287 (UK): *My mum is constantly cold whereas I am always warm, always arguing over the temperature.*

R6264 (Spain): *The "fight" continues in our family about manipulating thermostats in my house for the different perception of comfort among the members of the family unit.*

Still others mentioned instances of fighting with friends or even using heating systems to play jokes and pranks on each other:

R2022 (Germany): *Every time I enter a room, I turn on the heating in our*

Fig. 7. Stated sources of household tension and conflict over heat (n = 10,109). Panel A shows responses to the question that heating is likely to cause conflict with different classes of actors. Panel B shows the specific answer about conflicts with landlords organized by country.

apartment, every time my friend enters the room, he turns it down. It's kind of an eternal battle for room temperature between us hahaha

R320 (UK): *In summer my sibling turned it on high I sweat whole night and couldn't figure out why.*

R328 (UK): *If you run the hot tap in one room and someone is in the shower, the shower runs cold and you hear them scream.*

These comments all reflect a range of more personal interactions with heating systems or the people that use them, ranging from the deviant and illegal to the humorous, endearing and playful.

5. Temperature: heating preferences and satisfaction

This section explores our results concerning temperature preferences, how warm households reporting desiring their indoor climates for the summer and winter. It also examined how satisfied they were with their heating systems.

5.1. Temperature preferences

Fig. 8 depicts preferences for preferred (heating) temperature in the winter, with many respondents expressing 20° (26%), 22° (17%), and 21° (17%), but the rest (40%) preferring a great range of other temperatures, some as high as 30, others as low as 2. This could reflect a range of preferences or even a lack of knowledge about temperature. Either way, our respondents reported a great variation in preferred household temperature in the winter, with no single temperature occupying more than 26% of self-reported preferences. Preferences for very warm homes (greater than 25 Degrees) were the strongest in Spain (15%) and the UK (13.9%). Sweden stands out as perhaps the most reasonable country, with only 6.7% of respondents arguing homes would be excessively warm, followed by only 7.1% of German respondents.

A preference for at times extremely warm homes came out of our qualitative material as well. R1139 (UK) expressed satisfaction with warm temperatures by noting:

When we had friends over they made a joke that our home is always warm because we're trying to replicate life in the Caribbean.

R7032 (Spain) added that:

My children always complain that my house is too hot in winter, but I am in a T-shirt and shorts.

R9493 (Sweden) similarly said that:

We are used to high temperatures in winter indoors so you can have comfortable clothes type t-shirt and shorts. I always freeze indoors and everywhere here in Sweden.

R9070 (Sweden) even said they have no need for a temperature dial, control, or thermometer, noting:

I don't need a thermometer - I just see how much clothes I need to put on.

Some family norms went the other way, however, towards extremely cold or almost negligent levels of heat for their children. As R9262 (Sweden) admitted:

I had an oil pan in my childhood home. Dad was stingy and wanted to save on oil and firewood so I had 14° in my room one winter. This was also due to poorly insulated windows, my hair would blow indoors whenever it was windy.

Similarly divergent preferences were stated for preferred coolness in the summer, with no single temperature capturing more than 23% of respondents stated preferences. Preferred summer temperatures were even more distributed, with only 20% preferring 20° followed by 18° (15%) and 22° (8%). The remaining 57% all preferred at times drastically different summer temperatures.

5.2. Satisfaction and dissatisfaction

In terms of satisfaction, most respondents (more than half) were satisfied with their current heating and hot water system and 27.3% were very satisfied (see Fig. 9). The UK had the highest proportion of those satisfied to very satisfied (82.9%) followed by Spain (82.5%), Italy (80.5%) and Germany (80.5%). This high rate of in the UK—dominated by gas boilers of perceived high efficiency—may make it a difficult market for alternate heating systems of any time to penetrate. Conversely, even though they had the lowest-carbon heating system across the five countries, the Swedes were the most dissatisfied across all countries.

That said, a host of qualitative comments underscore just how bad people's heating systems are in practice:

R28 (UK): *My current heating system is a communal "hot air vent" system, grossly out of date, inefficient and just provides clouds of dust whenever it's switched on.*

R1172 (UK): *My heating system is rubbish and I always feel cold it's hilarious.*

R1608 (UK): *Heating system never worked so started fires.*

R5817 (Italy): *Once we had a boiler so bad we had to take a shower by boiling the water on the fire.*

Two respondents mentioned serious accidents related to their heat:

R1910 (UK): *Boiler exploded almost killed my friend when she was taking shower. Some people died in bath next door.*

R4107 (Italy): *Sometimes the boiler in our house would just stop working. We came home one day to find it had burnt our house to the ground.*

R2874 (Germany) spoke about a heating system so bad in the winter, they had to sit in the car (outside) to be warm:

One winter our heating failed, the apartments were cold, no technician could be reached, it was just the on and off button, we took turns in the house sitting outside in our Mercedes [automobile] to stay warm, otherwise everyone sat in thick clothes and waited their turn.

R4906 (Italy) had a clever strategy for dealing with "bad" or malfunctioning boilers, they stockpiled extra ones for redundancy:

I once had three boilers and one replaced the other in an emergency, now unfortunately it is no longer possible.

R10043 (Sweden) developed an intimate ritual of care needed to maintain heating.

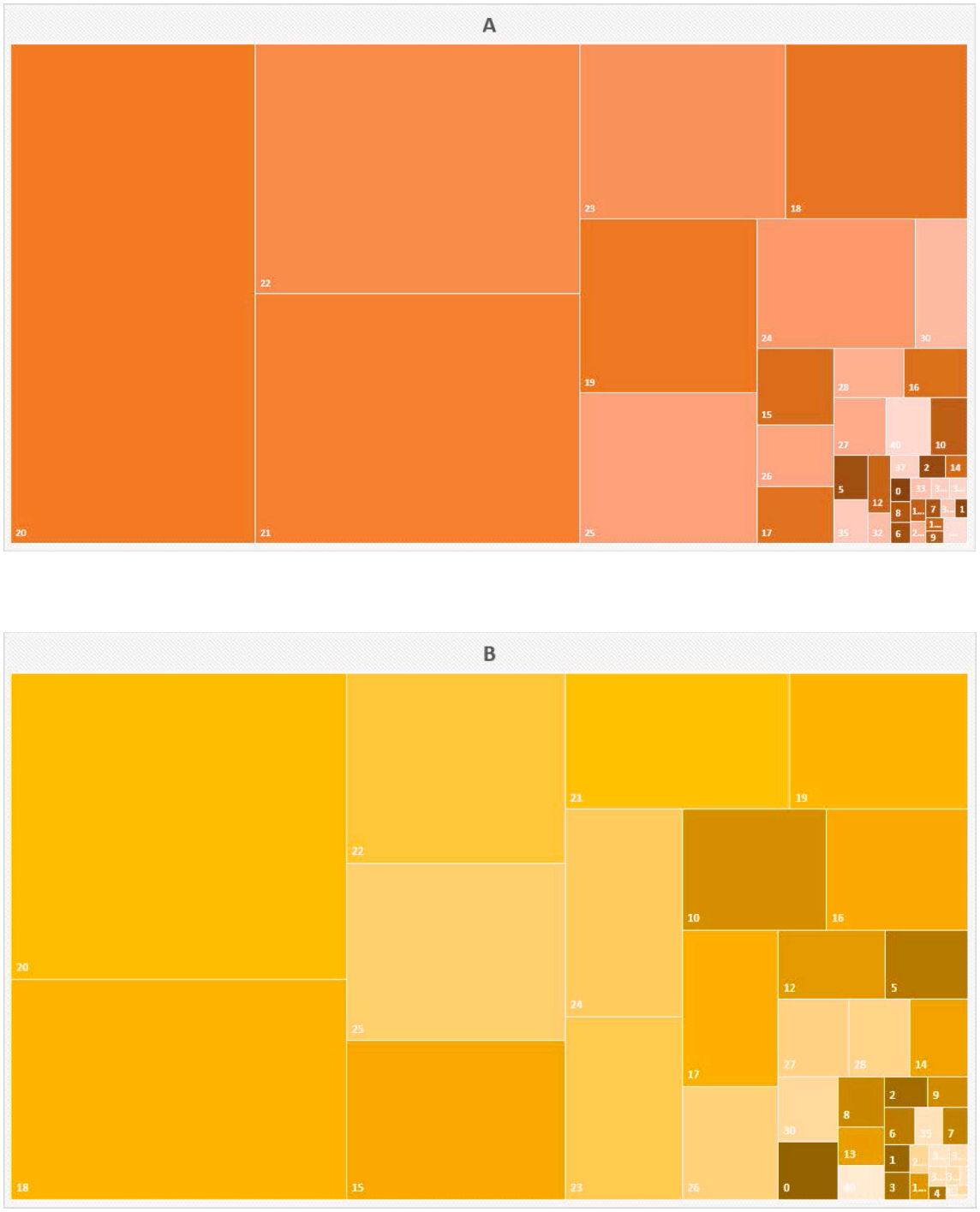

Fig. 8. Preferred temperatures in Celsius identified by respondents (n = 10,109). Panel A refers to preferred winter temperatures and Panel B preferred summer temperatures.

Unusually, you have to ventilate the elements once a week all the time otherwise the heat will disappear from them and the hot water takes an eternity before it arrives, you can flush the tap fully for up to 5 min. It gets old having to continually do this.

These statements firstly indicate just how "bad" people's heating is; in some cases not even functional yet alone optimal or low-carbon. Moreover, it reveals some of the ingenious coping strategies people utilize to deal with coldness, such as wearing thick clothing, sitting in heated cars, burning fires, or stockpiling spare parts.

6. Desirability of change: heating priorities, business models and trust

In this section, we explore the likelihood that respondents suggested they were to adopt low-carbon technologies or change their practices. This includes the desirable (and undesirable) attributes of low-carbon heat, as well as policies and business models (such as heat plans, heat as a service, and retrofits) alongside issues of trust.

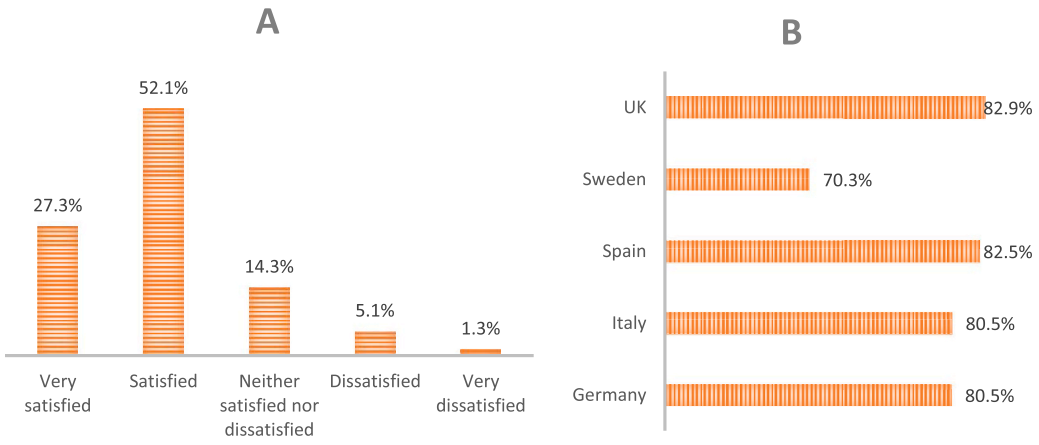

Fig. 9. Levels of satisfaction with current heating system (n = 10,109). Panel A shows stated satisfaction with current heating systems across the entire sample, Panel B high satisfaction organized by country.

6.1. Likelihood of changing or adopting new technology

We asked how likely respondents would be, if they were given the opportunity in the next few years, to change their heating to any number of fuels. In Fig. 10, you can see that most suggested they would prefer to switch to solar (32%) or gas (28%). Interestingly, hydrogen was one of the least favored options, being almost equal (11%) only to oil in its popularity across the countries. Solar heating in particular was most preferred in the UK (43.2%) and Germany (36.1%). We also asked respondents in open-ended financial terms how much extra they would be

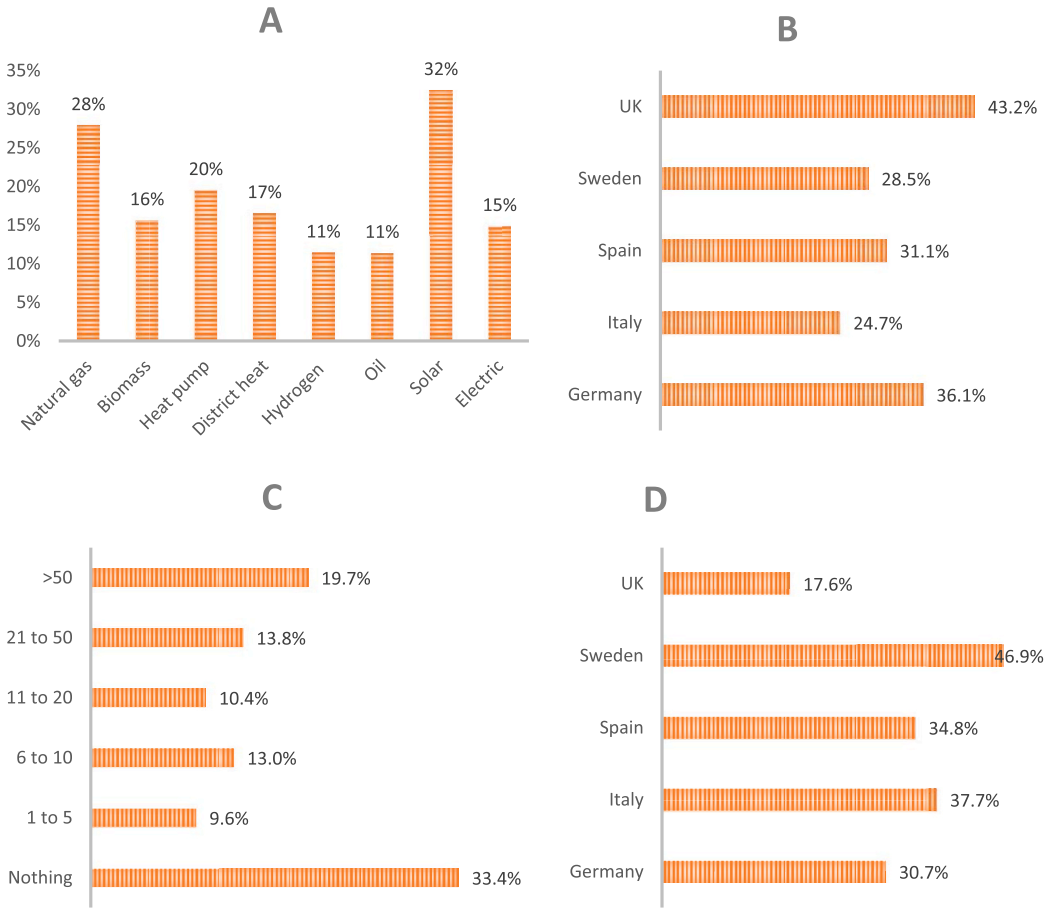

Fig. 10. Willingness to change heating or pay for low-carbon heat (n = 10,109). Panel A shows the likelihood of changing heat to different sources for the entire sample. Panel B shows respondents likely to very likely to adopt solar heating by country. Panel C how much extra respondents stated they would pay per month for low-carbon heat. Panel D shows by country how many would pay more than €20/month.

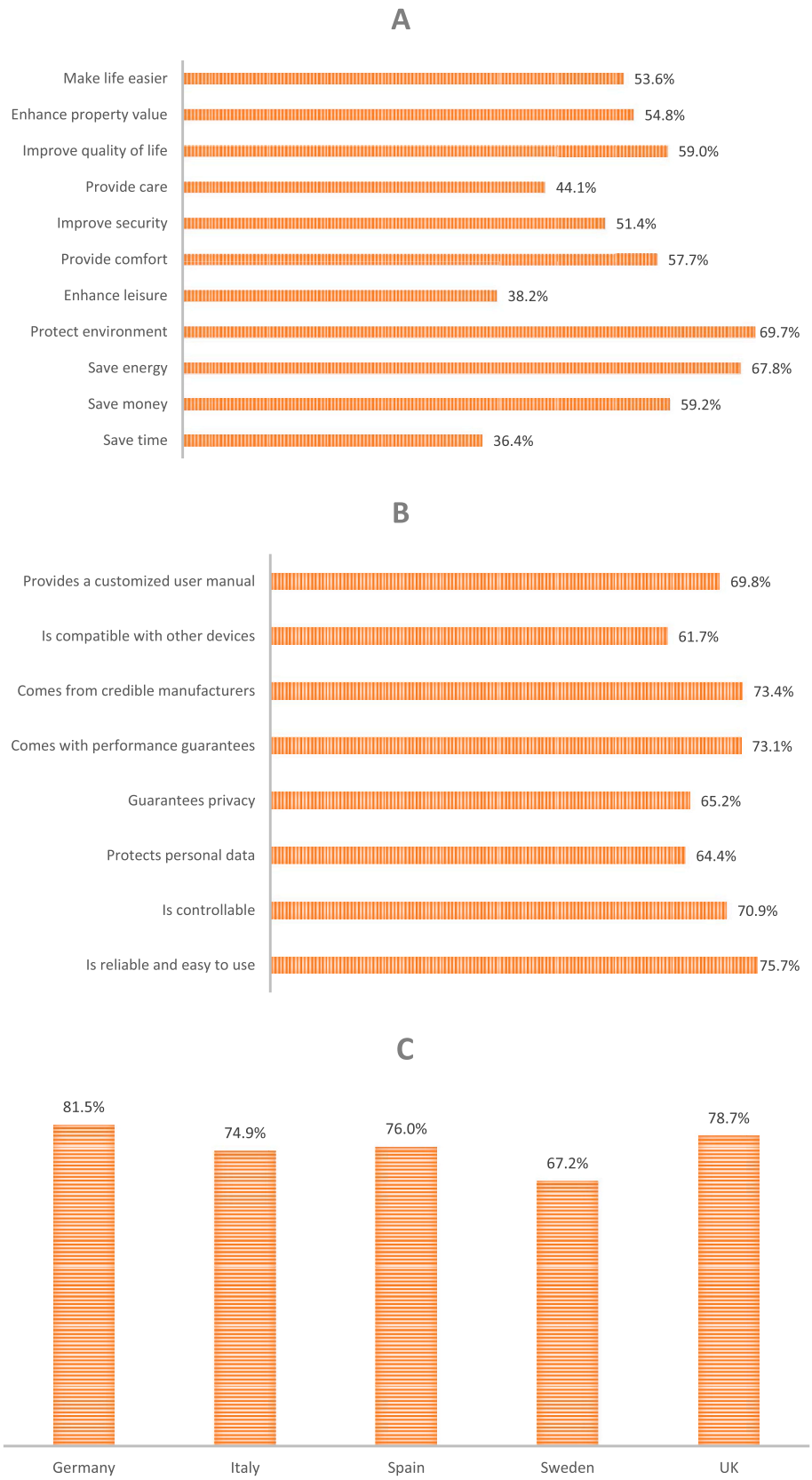

Fig. 11. Desirable attributes of low-carbon heat (n = 10,109). Panel A shows desired attributes for low-carbon heating specifically, across the entire sample. Panel B desired design parameters for such systems. Panel C respondents who believed that low-carbon heating needed to be easy and reliable organized by country. Source: Authors

willing to pay, per month in Euro, for low-carbon heat. Although one third (33.4%) said "nothing," one-fifth (19.7%) suggested more than €50, indicating the two poles of the spectrum. Almost half (46.9%) of Swedish respondents, and roughly one-third of Italian (37%), Spanish (35%), and German (31%) also indicated they would pay more than €20/month for low-carbon heat. At the extreme end of the spectrum, one German respondent stated they would pay €20,000/month for low-carbon heat and one Spanish and Swedish respondent each said they would pay €99,999 for low-carbon heat, the maximum number allowed by our survey, perhaps indicating a desire to capture the "infinite value" of mitigating climate change.

6.2. Valuable attributes of low-carbon heat

We asked respondents about the attributes they most valued about potential low-carbon heating systems with the results shown in Fig. 11, ranging from convenience (make life easier, 53.6%) to saving time (36.4%) to protecting the environment (69.7%). In terms of the operational features or performance criteria of a heating system, respondents highly rated all of the attributes we tested, including having an easy user manual and interoperability with other devices to strong manufacturer guarantees and reliability and ease of use (see Fig. 11).

As Fig. 11 indicates, reliability and ease of use were the highest preferred attributes, one that also was consistent across all five countries examined and consistent in our qualitative material. Indeed, there more than 100 respondents (!) mentioned heating systems breaking down on Christmas or during holidays, as R6751 (Spain) put it:

Our heating normally works well, but when we have had a fault in the boiler, it has been festive and cold dates, such as December 24, when there is no technician to repair it, and then for 2–3 days we are without heating and that is when we realize quickly the value of having heating at home.

R7474 (Spain) talked about reliability issues that crop up due to their boiler literally because of birds:

I have an individual diesel boiler to heat the house and it is necessary to clean the gas extraction duct every very short time since there are birds that sneak inside and then they cannot get out.

R10094 (Sweden) remarked how even their district heating system can have reliability problems:

The heat pipes broke and we were without heat for 1 month, went with winter clothes indoors in September month.

6.3. Business models

We explicitly tested perceptions and preferences for 8 emerging business models in the survey as well, framing them and offering slight definitions as follows:

- Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat)
- Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat)
- Warmth payment plan (e.g., charging a house for a set number of warm hours per month)
- Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting)
- Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed)
- Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee)
- Low-carbon heating retrofits
- Community contracts between neighbors (e.g. peer-to-peer energy trading)

None of these were strongly supported or supported by more than about a quarter of respondents (see Fig. 12), although retrofits (26%), bundled energy plans (24%), and heat as a service (23%) were the top three preferred business models within this family of business models. Surprisingly, support for P2P trading was not more prominent; even in the country with the highest percentage of preferences, this peaked at only 22.9% of our survey sample. Indeed, at least in Italy, P2P contracts became theoretically feasible on February 2020 without a technical regulation clarifying their practical aspects. At the time of the survey, most participants still did not likely know about their existence, and this was probably reflected in their answers.

6.4. Trust

Most values, beliefs, and even perceptions and preferences do not exist by themselves, but are shaped by the statements of others (what

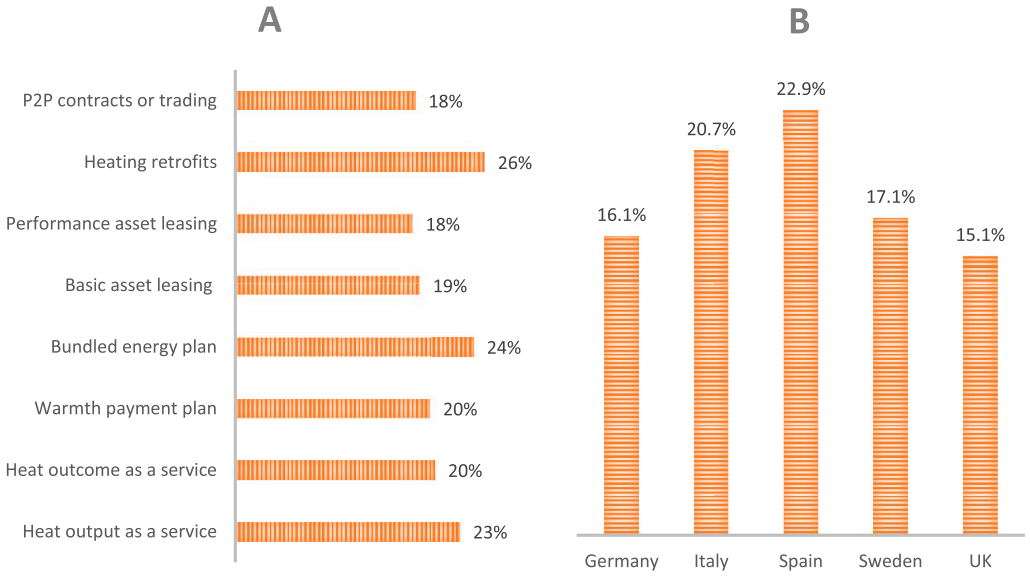

Fig. 12. Desirability of various heating business models and peer-to-peer trading (n = 10,109). Panel A shows responses across the entire sample, people answering "I would support business models related to …" Panel B shows responses to "I am interested in P2P heat trading" organized by country.

others know), making communication and trustworthiness essential factors in how people make decisions and consume information [17–19]. In terms of who might implement these business models, steer and shape them, or otherwise disseminate information (or even knowledge) about them, across the entire sample the most trustworthy entities were deemed to be technology suppliers (54%) and professionals such as architects, engineers, and technicians (53%), but *not* social media (22%), traditional media (29%), or even friends (39%) (see Fig. 13). This has some potentially profound implications for communication and marketing activities, especially as it implies that self-rated trust is lower among friends, neighbors, and family than government. (This finding also buttresses the one above about relative disinterest in peer-to-peer trading, as homes likely would not want to trade energy with those they do not trust). It lastly speaks to the powerful credibility that our respondents seem to enshrine in tradespersons and professionals. Within the countries, the Italians and English were most likely to trust only themselves; the Italians and Spanish had more trust in scientists and researchers; and the German and English had the least trust in government.

It is particularly striking that energy suppliers were the fourth most trusted entities out of the 13 categories (at slightly less than 51%) we mentioned in the survey, coming only after technology suppliers (54%), professionals (53%) and Scientists (51%). This is because in our qualitative data, about a third of the open-ended comments (from more than 1300 respondents) actually were complaints about either heat and energy providers or installers and engineers. R37 (UK) wrote:

The electricity has gone rogue. Teleswitch box provided by Northwest Electricity that should be economy has been playing up but North West electricity refusing responsibility. Our home is now freezing cold and North West electricity doesn't give a damn.

R219 (UK) declared:

My boiler stopped working. British Gas claimed it could not be repaired

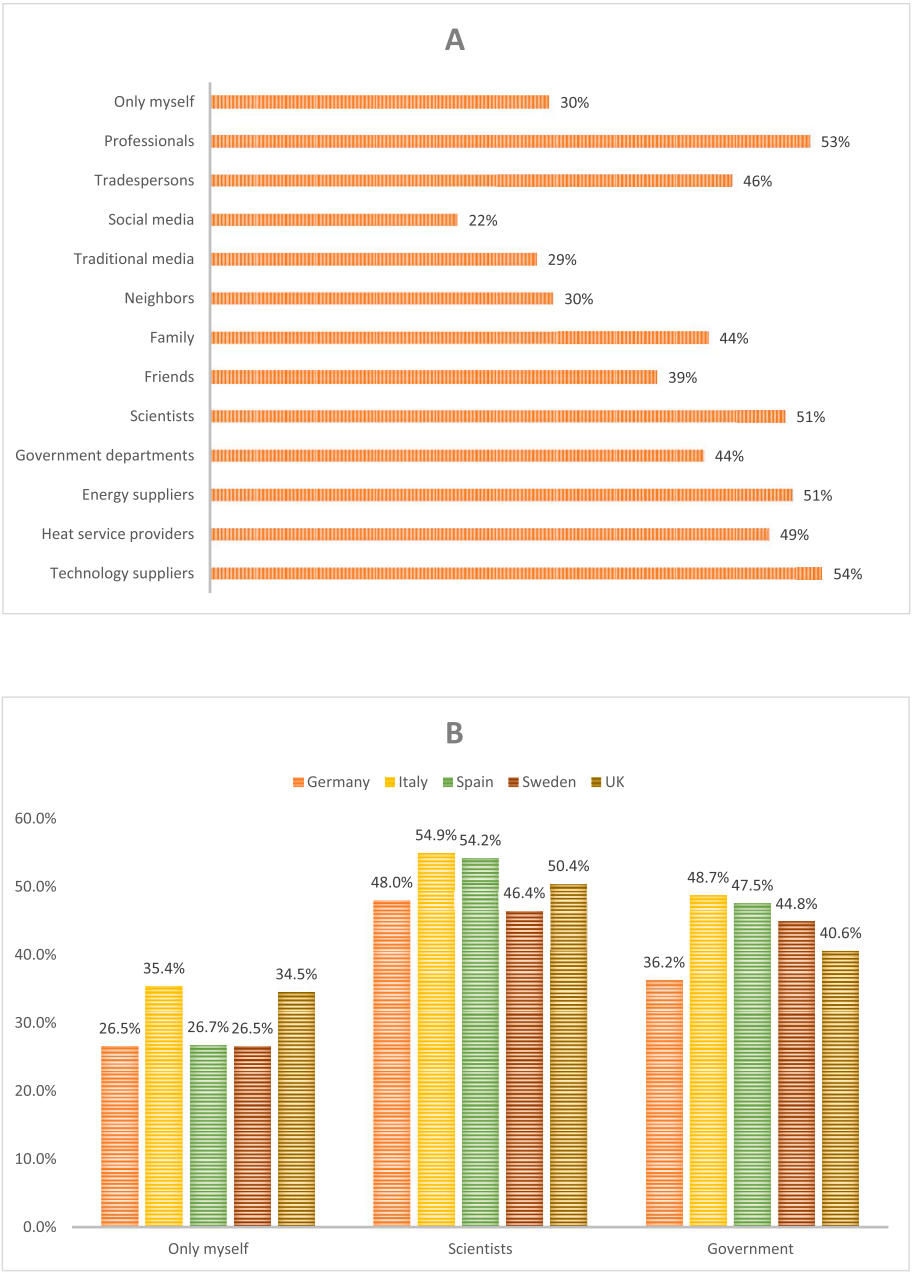

Fig. 13. Levels of trust in various heating actors and institutions (n = 10,109). Panel A shows responses across the entire sample to "I find the following actors trustworthy," Panel B answers to "I trust …" organized by country.

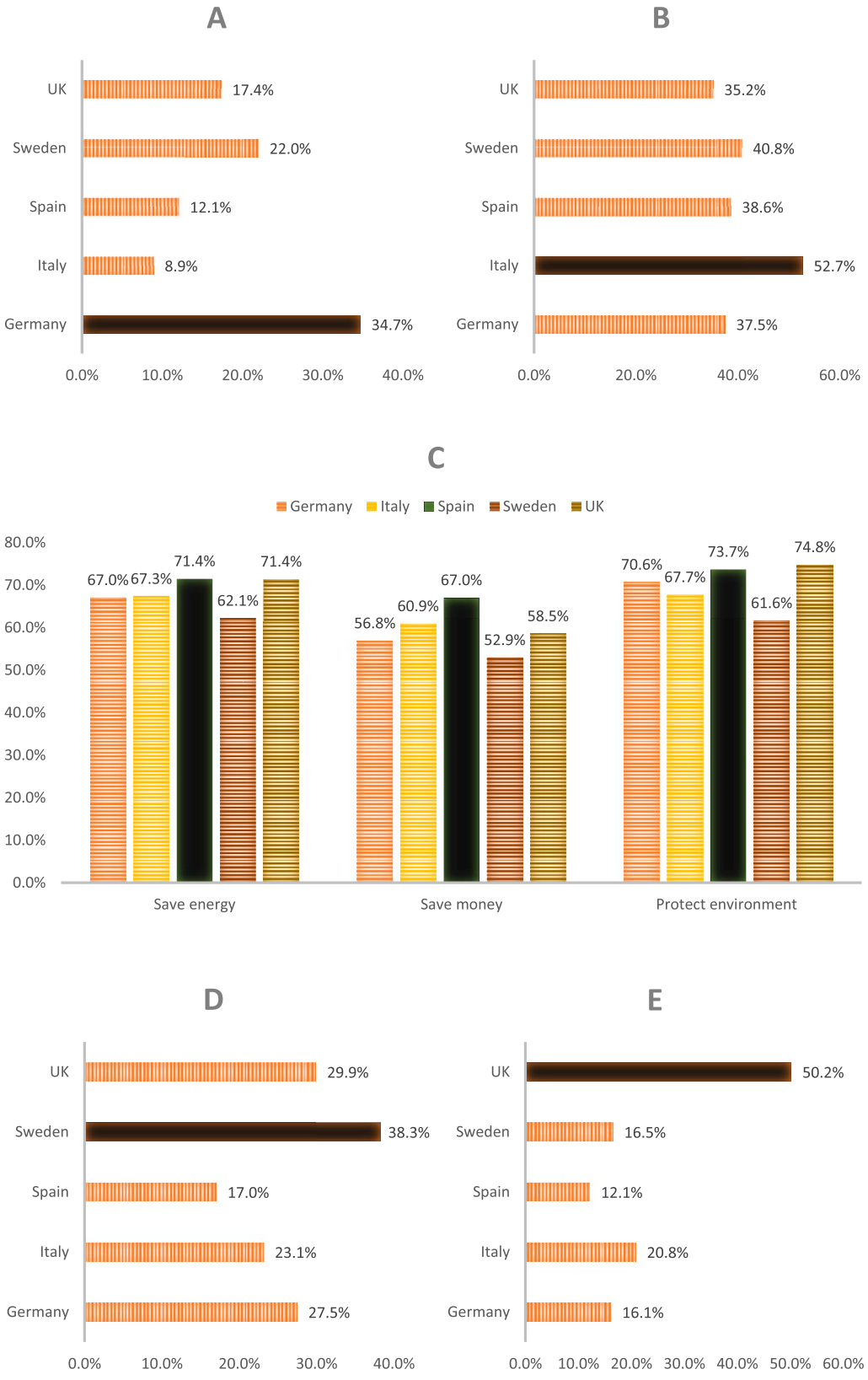

Fig. 14. Country outliers for heating practices, preferences, and desirable attributes (n = 10,109). Panel A shows responses by country for preferences for heating all year round. Panel B for heating every room, Panel C desirable attributes to low-carbon heating. Panel D shows heating for pets, Panel E that homes should be 17° Celsius or cooler.

Table 1
German purposes, preferences, and practices of heat compared to all other countries.

Questions		All respondents (N = 10,109)	Country groups	
			Germany (N = 2009)	Non-Germany (N = 8100)
Knowledge[a]*	Knowledge about how home and water is heated	2.87	2.77	2.90
Attention to heat[a]*	Attention paid to the amount of heat used in the home	2.97	2.94	2.98
Satisfaction[b]*	Overall satisfaction with heating and hot water system	3.99	3.99	3.99
Control[a]*	Level of control over current heating and hot water system	2.49	2.65	2.45
Who controls household heating and hot water system[c]**	Myself	7168	1484	5684
	My partner	3443	681	2762
	My children	561	130	431
	Other family members	913	155	758
	Guests and visitors	102	47	55
	Maintenance person or technician	1424	304	1120
	Others	167	40	127
Temperature[d]*	Home temperature during winter	21.21	21.28	21.19
	Home temperature during summer	19.43	19.78	19.35
Common or acceptable heating practices[b]*	OK to keep heat on all year round	2.04	2.24	1.99
	OK to keep heat on all day during winter	3.08	3.51	2.97
	Necessary to keep heat on for pets in the home	2.71	2.79	2.69
	Necessary to keep heat on to improve health	3.12	3.07	3.13
	Necessary to keep heat on for the health of the building	3.13	3.37	3.07
	Necessary in winter to occasionally open windows for fresh air	4.11	4.40	4.03
	Necessary to heat every room to maintain a warm household	3.15	3.06	3.18
	Heating is the most important energy service in the home	3.64	3.78	3.60
	Home should be warm enough in winter to wear comfortable clothing indoors (e.g. shorts and t-shirts)	3.01	3.00	3.01
Heating technologies could lead to conflict between[b]*	Housemates	2.66	2.20	2.78
	Couples and partners	2.68	2.31	2.76
	Children and parents	2.63	2.26	2.73
	Landlords and tenants	2.89	2.52	2.98
	Hosts and guests	2.43	2.06	2.53
	Neighbors	2.27	1.95	2.35
Likely to change heating source to another one[b]*	Gas	2.82	2.51	2.89
	Biomass boiler	2.28	2.12	2.32
	Heat pump	2.52	2.31	2.57
	District heating	2.36	2.26	2.38
	Hydrogen	2.14	2.00	2.18
	Oil/fuel oil/LPG	2.02	1.96	2.03
	Solar	2.91	2.65	2.97
	Resistive/electric heating	2.29	1.95	2.37
Current payment type for heating, hot water and cooling services[c]	Pay for the volume of electricity or gas in individual boiler and/or air con system	5293	786	4507
	Pay for the volume of hot water, heat and or cooling use in the home from a centralized system (either in the building or a heat/cooling network)	2156	653	1503
	Pay for the internal temperature level in the home and the building manager takes care of the heating/cooling system	841	289	552
	Don't know	1335	226	1109
	Other	484	55	429
Desired benefits of low-carbon heating technologies are[b]*	Save time	3.36	3.11	3.42
	Save money	3.88	3.79	3.90
	Save energy	4.13	4.07	4.14
	Save the environment	4.20	4.19	4.21
	Enhance leisure	3.43	3.19	3.49
	Provide comfort	3.82	3.65	3.86
	Improve security	3.74	3.69	3.75
	Provide care	3.55	3.03	3.68
	Improve quality of life	3.88	3.71	3.92
	Increase property value	3.80	3.77	3.81
	Make life easier	3.77	3.59	3.82
For usability of heating technologies, it is important that they[b]*	Are reliable and easy to use	4.28	4.34	4.26
	Can be controlled and over-ridden	4.12	4.02	4.15
	Protect personal data/information	4.04	4.08	4.03
	Guarantee privacy and confidentiality	4.05	4.11	4.04
	Come with performance warranties	4.23	4.20	4.23
	Are made by credible manufacturers	4.22	4.20	4.23
	Are compatible with other devices in the home	3.93	3.68	4.00
	They are provided with a customized user manual for beginners	4.13	3.97	4.17
Emerging business models[b]*	Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat)	2.72	2.72	2.72
	Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat)	2.70	2.73	2.70
	Warmth payment plan (e.g., charging a house for a set number of warm hours per month)	2.59	2.50	2.61
	Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting)	2.79	2.65	2.83
		2.58	2.50	2.61

(*continued on next page*)

Table 1 (*continued*)

Questions		All respondents (N = 10,109)	Country groups	
			Germany (N = 2009)	Non-Germany (N = 8100)
	Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed …			
	Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee)	2.59	2.52	2.61
	Low-carbon heating retrofits	2.84	2.75	2.87
	Community contracts between neighbors (e.g. peer-to-peer energy trading)	2.58	2.51	2.60
Who is trustworthy in heating technologies[b]*	Technology suppliers (e.g. Vaillant or Siemens)	3.72	3.87	3.69
	Heat service providers (e.g., energy service companies)	3.58	3.61	3.57
	Energy suppliers (e.g. EDF or British Gas)	3.59	3.56	3.60
	Government departments (Department for Business, Energy & Industrial Strategy, Federal Ministry for Economic Affairs and Energy)	3.43	3.24	3.48
	Researchers and scientists (universities)	3.65	3.56	3.67
	Friends	3.37	3.38	3.37
	Family	3.48	3.52	3.47
	Neighbors	3.15	3.14	3.15
	Traditional media (newspapers, TV)	3.06	3.10	3.05
	Social media (Twitter, Facebook, Instagram)	2.73	2.54	2.78
	Tradespersons (builder, plumber, gas fitter)	3.50	3.41	3.52
	Professionals (architects, engineers, technicians, etc.)	3.65	3.67	3.65
	Nobody but myself	3.10	2.97	3.13

* Mann Whitney *U* test.
**Chi-Square Color highlight indicates significant at $p < .05$.
Notes.
[a] Reported as mean values of 4-point Likert type questions (e.g. 1 = Nothing at all to 4 = A lot).
[b] Reported as mean values of 5-point Likert type questions (e.g. 1 = Strongly disagree to 5 = Strongly agree; 1 = Very unlikely to 5 = Very likely; "Don't know"s have been reported as missing values).
[c] Count is frequency to those selecting the answer.
[d] Temperature reported as mean degrees in Celsius.

and that I needed to replace it. They were wrong: the gas supply wasn't working due a faulty meter.

R313 (UK) said:

Currently I am with EDF - They usually do not bill me correctly and I would class them as untrustworthy.

R460 (UK) added:

Boiler backed up. British Gas took two weeks to solve problem, coming time and time again with different spares. It was a spider in a flue pipe.

R7746 (Spain) lastly noted:

I am against large energy companies such as Iberdrola, which operate in a strategically unfair way.

Another collection of responses supports the contention that family, neighbors, and friends are not to be trust. R427 (UK) suggested:

Make sure you put a lock on your oil tank! Otherwise your neighbors will steal it.

R432 (UK) was even pithier:

Trust no one but yourself.

7. Culture: country and national variation

Interestingly, and shown in Fig. 14, there were fairly large differences in responses country by country that arose from our findings as well. This includes the finding that Germans are far more likely to heat all year round. Italians are far more likely to heat every room. Saving money from heating systems was far more preferred in Spain. Swedes are far more likely to desire heat for their pets. British respondents prefer very cool temperatures.

7.1. Germany

In Table 1, we report statistically significant differences in responses between Germany and the other four countries. When disaggregated by country, Germany was surprisingly the "worst" with 34.7% of respondents indicating this was acceptable heating behavior to heat all year round compared to 22% or less across all other countries. This, again, reveals a possible paradox as Germany is often promoted as an exemplar of renewable energy diffusion, energy sustainability, and environmental awareness about energy [20,21]. German respondents were also fans of opening the windows in the winter compared to the other countries, and they also more strongly viewed heating as the most important energy service in a household (see Table 2).

As a possible explanation for some of these results, in more than 90% of homes in Germany, both heating and domestic hot water are typically supplied by one and the same heating appliance. Shutting down the heating appliance is, therefore, not possible during summer as hot water is needed all year round. Other Germans may have vacation houses and prefer to keep those heated to avoid damaging the building. Moreover, many Germans prefer to open or tilt the windows in winter to get fresh air and are quite resistant to restrict ventilation rules like carrying out shock ventilation for short periods in the morning and evening instead of tiling the windows. Even in passive energy houses with ventilation systems and heat recovery, the literature suggests that Germans feel they do not have enough fresh air and must open windows to compensate [22].

7.2. Italy

Italy deviates from our full sample and other countries in interesting ways as well. Italian respondents consider themselves very knowledgeable about heat and hot water, consistently with other studies about indoor thermal control [23]. They report more direct control over their heating systems. They believe heating is important for health and also that freshness is desirable in the winter by opening windows. Indeed, more than half (52.7%) of Italians believe they need to heat every room. They lastly favored retrofits far more than other country groups, perhaps since building retrofit is considered a common action, and construction output has decreased in the past few years [24].

As an explanation, in Italy most homes still have one boiler for both direct hot water and space heating, but may operate the system to be completely separated (through thermostats or simple on-off on the space

Table 2
Italian purposes, preferences, and practices of heat compared to all other countries.

Questions		All respondents (N = 10,109)	Country groups	
			Italy (N = 2039)	Non-Italy (N = 8070)
Knowledge[a], *	Knowledge about how home and water is heated	2.87	3.14	2.81
Attention to heat[a], *	Attention paid to the amount of heat used in the home	2.97	3.33	2.88
Satisfaction[b]*	Overall satisfaction with heating and hot water system	3.99	3.99	3.99
Control[a]*	Level of control over current heating and hot water system	2.49	2.53	2.48
Who controls household heating and hot water system[c]**	Myself	7168	1478	5690
	My partner	3443	708	2735
	My children	561	130	431
	Other family members	913	264	649
	Guests and visitors	102	13	89
	Maintenance person or technician	1424	173	1251
	Others	167	15	152
Temperature[d]*	Home temperature during winter	21.21	21.03	21.25
	Home temperature during summer	19.43	20.73	19.11
Common or acceptable heating practices[b]*	OK to keep heat on all year round	2.04	1.66	2.14
	OK to keep heat on all day during winter	3.08	2.36	3.26
	Necessary to keep heat on for pets in the home	2.71	2.60	2.73
	Necessary to keep heat on to improve health	3.12	3.36	3.05
	Necessary to keep heat on for the health of the building	3.13	3.23	3.11
	Necessary in winter to occasionally open windows for fresh air	4.11	4.25	4.07
	Necessary to heat every room to maintain a warm household	3.15	3.49	3.07
	Heating is the most important energy service in the home	3.64	3.46	3.68
	Home should be warm enough in winter to wear comfortable clothing indoors (e.g. shorts and t-shirts)	3.01	2.73	3.08
Heating technologies could lead to conflict between[b]*	Housemates	2.66	2.87	2.61
	Couples and partners	2.68	2.77	2.65
	Children and parents	2.63	2.79	2.60
	Landlords and tenants	2.89	2.99	2.86
	Hosts and guests	2.43	2.67	2.38
	Neighbors	2.27	2.44	2.23
Likely to change heating source to another one[b]*	Gas	2.82	3.33	2.69
	Biomass boiler	2.28	2.58	2.20
	Heat pump	2.52	2.79	2.45
	District heating	2.36	2.52	2.32
	Hydrogen	2.14	2.49	2.06
	Oil/fuel oil/LPG	2.02	2.14	1.98
	Solar	2.91	3.28	2.81
	Resistive/electric heating	2.29	2.50	2.24
Current payment type for heating, hot water and cooling services[c]	Pay for the volume of electricity or gas in individual boiler and/or air con system	5293	1328	3965
	Pay for the volume of hot water, heat and or cooling use in the home from a centralized system (either in the building or a heat/cooling network)	2156	382	1774
	Pay for the internal temperature level in the home and the building manager takes care of the heating/cooling system	841	107	734
	Don't know	1335	189	1146
	Other	484	33	451
Desired benefits of low-carbon heating technologies are[b]*	Save time	3.36	3.49	3.32
	Save money	3.88	3.94	3.87
	Save energy	4.13	4.12	4.13
	Save the environment	4.20	4.21	4.20
	Enhance leisure	3.43	3.76	3.35
	Provide comfort	3.82	3.94	3.79
	Improve security	3.74	3.99	3.68
	Provide care	3.55	3.78	3.50
	Improve quality of life	3.88	4.03	3.84
	Increase property value	3.80	3.91	3.77
	Make life easier	3.77	3.91	3.74
For usability of heating technologies, it is important that they[b]*	Are reliable and easy to use	4.28	4.23	4.29
	Can be controlled and over-ridden	4.12	4.10	4.13
	Protect personal data/information	4.04	4.00	4.05
	Guarantee privacy and confidentiality	4.05	4.02	4.06
	Come with performance warranties	4.23	4.26	4.22
	Are made by credible manufacturers	4.22	4.22	4.22
	Are compatible with other devices in the home	3.93	4.04	3.91
	They are provided with a customized user manual for beginners	4.13	4.20	4.11
Emerging business models[b]*	Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat)	2.72	2.85	2.69
	Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat)	2.70	2.84	2.67
	Warmth payment plan (e.g., charging a house for a set number of warm hours per month)	2.59	2.72	2.56
	Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting)	2.79	2.86	2.77
		2.58	2.69	2.56

(*continued on next page*)

Table 2 (*continued*)

Questions		All respondents (N = 10,109)	Country groups	
			Italy (N = 2039)	Non-Italy (N = 8070)
	Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed …			
	Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee)	2.59	2.67	2.57
	Low-carbon heating retrofits	2.84	2.95	2.82
	Community contracts between neighbors (e.g. peer-to-peer energy trading)	2.58	2.66	2.56
Who is trustworthy in heating technologies[b]*	Technology suppliers (e.g. Vaillant or Siemens)	3.72	3.75	3.72
	Heat service providers (e.g., energy service companies)	3.58	3.66	3.56
	Energy suppliers (e.g. EDF or British Gas)	3.59	3.66	3.57
	Government departments (Department for Business, Energy & Industrial Strategy, Federal Ministry for Economic Affairs and Energy)	3.43	3.54	3.40
	Researchers and scientists (universities)	3.65	3.72	3.64
	Friends	3.37	3.29	3.39
	Family	3.48	3.44	3.49
	Neighbors	3.15	3.06	3.17
	Traditional media (newspapers, TV)	3.06	3.05	3.06
	Social media (Twitter, Facebook, Instagram)	2.73	2.90	2.69
	Tradespersons (builder, plumber, gas fitter)	3.50	3.55	3.49
	Professionals (architects, engineers, technicians, etc.)	3.65	3.67	3.65
	Nobody but myself	3.10	3.24	3.06

* Mann Whitney *U* test.
**Chi-Square Color highlight indicates significant at $p < .05$.
Notes.
[a] Reported as mean values of 4-point Likert type questions (e.g. 1 = Nothing at all to 4 = A lot).
[b] Reported as mean values of 5-point Likert type questions (e.g. 1 = Strongly disagree to 5 = Strongly agree; 1 = Very unlikely to 5 = Very likely; "Don't knows" have been reported as missing values).
[c] Count is frequency to those selecting the answer.
[d] Temperature reported as mean degrees in Celsius.

heating system). Hot water may have a dedicated system with a storage for each bathroom in very old houses, and this is typically electrically driven. Only in new construction, which captures less than 10% of the housing market over the past decade [24], have thermostats been positioned in all thermal zones of a house, enabling possible enhanced heating control. Lastly, it is interesting to note that, despite the general slow trends of the Italian construction sector, Italians seem more willing to change their heating system, especially to a new gas boiler or a solar heating system.

7.3. Spain

Given Spain's more moderate climate, respondents suggested lower means for preferred winter and summer temperatures, and Spanish respondents were less likely to heat all the time in the winter and to heat for pets. As shown in Table 3, Spanish respondents also rated lower the aspects of heating for health or heating for the strength of a building. In terms of country preference, saving energy was far more preferred in Spain (71.4%) and the UK (71.4%) than in Sweden; saving money was far more preferred (67%) in Spain as well than in all other countries. Also, the mean rank of conflicts among housemates overheat was much higher in Spain than in the other countries. Spain lastly had the highest reported scores about household willingness to try out new heating systems.

As an explanation, Spanish households may think that it is cheaper to switch off the heating system when going to bed or when leaving the house to go to work and switching it on when arriving home in the evening that to keep the heating on all day. Most Spanish households have a gas boiler for heating and domestic hot water and a thermostat in the living room for temperature control; the gas boiler allows changing from winter mode (heating and domestic hot water) to summer mode (only domestic hot water), usually the change is done in April–May and in November by the user. The fact that usually only one thermostat is available in most households could explain the higher rate of conflicts in the household due to thermal comfort, especially if one part of the house/apartment is facing south and the other north, which could mean very different indoor temperatures due to passive sun heating even in the winter season. The higher thermal discomfort and higher household conflicts could explain the higher willingness of Spaniards for a change in the heating system, but probably also the perception that heating is expensive and finding cheaper options is a need. Moreover, just recently Spanish people have started to wear t-shirts in winter, so lower heating temperatures used to up to now are allowed if light sweaters are used; but these low temperatures could also be due to the perception of the high cost of heating and the strong media campaign undertaken in the last years showing that decreasing 1 °C the indoor temperatures means 8% less gas use and, therefore, cheaper heating bills.

7.4. Sweden

More than one-third (38.3%) of Swedish respondents stated they needed to heat for pets even though Veterinarians have indicated such heating is not necessary. This perception that pets need warm homes not only shows lack of possible heat literacy. It could also be that people in colder climates such as Sweden think more about the need for heating pets and they expect and experience harsher winters. In addition, we see the Swedes having some of the lowest numbers of stated control over their heating systems as a result, which might be interpreted as the different perception of control embedded in the culture. Swedes report far less knowledge about heat than the other countries, much lower attention to heat, and higher scores for believing in the necessity of heating for the strength of the building. Apart from landlords and tenants, Sweden has significantly much lower average scores for other forms of heating conflict, which might be attributed to its consensus-oriented culture. They were lastly less concerned about issues such as privacy and trust.

As a further explanation, in Sweden, most of the buildings are heated either by district heating or electrically driven heating (and cooling) system such as heat pumps. For district heating, when the average temperature over the day is higher than 16 °C, the pump for the district

Table 3
Spanish purposes, preferences, and practices of heat compared to all other countries.

Questions		All respondents (N = 10,109)	Country groups	
			Spain (N = 2038)	Non-Spain (N = 8071)
Knowledge[a]*	Knowledge about how home and water is heated	2.87	2.90	2.87
Attention to heat[a]*	Attention paid to the amount of heat used in the home	2.97	3.03	2.95
Satisfaction[b]*	Overall satisfaction with heating and hot water system	3.99	4.06	3.97
Control[a]*	Level of control over current heating and hot water system	2.49	2.40	2.51
Who controls household heating and hot water system[c]**	Myself	7168	1578	5590
	My partner	3443	893	2550
	My children	561	139	422
	Other family members	913	215	698
	Guests and visitors	102	5	97
	Maintenance person or technician	1424	170	1254
	Others	167	37	130
Temperature[d]*	Home temperature during winter	21.21	21.83	21.05
	Home temperature during summer	19.43	20.87	19.07
Common or acceptable heating practices[b]*	OK to keep heat on all year round	2.04	1.79	2.11
	OK to keep heat on all day during winter	3.08	2.42	3.24
	Necessary to keep heat on for pets in the home	2.71	2.19	2.84
	Necessary to keep heat on to improve health	3.12	2.49	3.28
	Necessary to keep heat on for the health of the building	3.13	2.22	3.37
	Necessary in winter to occasionally open windows for fresh air	4.11	4.04	4.12
	Necessary to heat every room to maintain a warm household	3.15	3.03	3.18
	Heating is the most important energy service in the home	3.64	3.42	3.69
	Home should be warm enough in winter to wear comfortable clothing indoors (e.g. shorts and t-shirts)	3.01	2.87	3.05
Heating technologies could lead to conflict between[b]*	Housemates	2.66	2.87	2.61
	Couples and partners	2.68	2.78	2.65
	Children and parents	2.63	2.80	2.59
	Landlords and tenants	2.89	2.92	2.88
	Hosts and guests	2.43	2.49	2.42
	Neighbors	2.27	2.56	2.20
Likely to change heating source to another one[b]*	Gas	2.82	3.02	2.77
	Biomass boiler	2.28	2.30	2.28
	Heat pump	2.52	2.43	2.55
	District heating	2.36	2.24	2.39
	Hydrogen	2.14	2.09	2.16
	Oil/fuel oil/LPG	2.02	2.04	2.01
	Solar	2.91	3.03	2.88
	Resistive/electric heating	2.29	2.55	2.22
Current payment type for heating, hot water and cooling services[c]	Pay for the volume of electricity or gas in individual boiler and/or air con system	5293	1363	3930
	Pay for the volume of hot water, heat and or cooling use in the home from a centralized system (either in the building or a heat/cooling network)	2156	356	1800
	Pay for the internal temperature level in the home and the building manager takes care of the heating/cooling system	841	70	771
	Don't know	1335	147	1188
	Other	484	102	382
Desired benefits of low-carbon heating technologies are[b]*	Save time	3.36	3.68	3.27
	Save money	3.88	4.09	3.83
	Save energy	4.13	4.23	4.10
	Save the environment	4.20	4.32	4.18
	Enhance leisure	3.43	3.45	3.43
	Provide comfort	3.82	4.02	3.77
	Improve security	3.74	4.07	3.65
	Provide care	3.55	3.96	3.44
	Improve quality of life	3.88	4.16	3.80
	Increase property value	3.80	3.89	3.78
	Make life easier	3.77	4.01	3.71
For usability of heating technologies, it is important that they[b]*	Are reliable and easy to use	4.28	4.31	4.27
	Can be controlled and over-ridden	4.12	4.23	4.10
	Protect personal data/information	4.04	4.13	4.01
	Guarantee privacy and confidentiality	4.05	4.15	4.02
	Come with performance warranties	4.23	4.26	4.22
	Are made by credible manufacturers	4.22	4.28	4.21
	Are compatible with other devices in the home	3.93	4.11	3.89
	They are provided with a customized user manual for beginners	4.13	4.24	4.10
Emerging business models[b]*	Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat)	2.72	2.91	2.67
	Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat)	2.70	2.80	2.68
	Warmth payment plan (e.g., charging a house for a set number of warm hours per month)	2.59	2.82	2.53
	Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting)	2.79	3.01	2.73
		2.58	2.79	2.53

(*continued on next page*)

Table 3 (*continued*)

Questions		All respondents (N = 10,109)	Country groups	
			Spain (N = 2038)	Non-Spain (N = 8071)
	Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed …			
	Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee)	2.59	2.76	2.54
	Low-carbon heating retrofits	2.84	3.07	2.78
	Community contracts between neighbors (e.g. peer-to-peer energy trading)	2.58	2.73	2.54
Who is trustworthy in heating technologies[b]*	Technology suppliers (e.g. Vaillant or Siemens)	3.72	3.78	3.71
	Heat service providers (e.g., energy service companies)	3.58	3.63	3.57
	Energy suppliers (e.g. EDF or British Gas)	3.59	3.68	3.57
	Government departments (Department for Business, Energy & Industrial Strategy, Federal Ministry for Economic Affairs and Energy)	3.43	3.50	3.41
	Researchers and scientists (universities)	3.65	3.71	3.64
	Friends	3.37	3.38	3.37
	Family	3.48	3.52	3.47
	Neighbors	3.15	3.20	3.13
	Traditional media (newspapers, TV)	3.06	3.10	3.05
	Social media (Twitter, Facebook, Instagram)	2.73	2.91	2.68
	Tradespersons (builder, plumber, gas fitter)	3.50	3.59	3.48
	Professionals (architects, engineers, technicians, etc.)	3.65	3.71	3.64
	Nobody but myself	3.10	2.97	3.13

* Mann Whitney *U* test.
**Chi-Square Color highlight indicates significant at $p < .05$.
Notes.
[a] Reported as mean values of 4-point Likert type questions (e.g. 1 = Nothing at all to 4 = A lot).
[b] Reported as mean values of 5-point Likert type questions (e.g. 1 = Strongly disagree to 5 = Strongly agree; 1 = Very unlikely to 5 = Very likely; "Don't knows" have been reported as missing values).
[c] Count is frequency to those selecting the answer.
[d] Temperature reported as mean degrees in Celsius.

heating is turned off and when the average daily temperature goes lower than 16 °C, the pump will be turned on automatically. This means the residents do not have to turn on or off anything in their heating system. Similarly, for the buildings which are heated by heat pumps, they do not need to turn off their heat pump during summer as it is also used for direct hot water production. So, the residents do not turn off the heating system any time of the year. Therefore, we hypothesize that there might be some misunderstanding on what "keep heating on" would mean. Occupants residing in rented apartments where heating is a hidden part of a monthly fee would have even less of an incentive for proficient or sustainable heating use. Sweden is also a heating regime dominated by little public resistance or involvement, and strong support for incumbent firms and a natural monopoly on district heating [25] (see Table 4).

7.5. United Kingdom

Table 5 offers a high-level summary of statistically meaningful differences in responses between UK residents and the other countries. UK respondents reported being more knowledgeable about heat and desiring more control. They also had higher degrees of satisfaction, and to heat every room. Data and privacy issue were rated as more significant in the UK as well. UK respondents tend to trust friends, family and neighbors more, compared to the others. UK respondents also reported trusting themselves more, perhaps fitting in with a mentality of "being the king of their castle". The heating market is more dominated by gas in the UK as well, because of (in part) a government action in the 1990s to enhance the energy efficiency in the building sector in addition to campaigns in the 1960s and 1970s to convert homes from town gas to natural gas [17]

Table 4
Swedish purposes, preferences, and practices of heat compared to all other countries.

Questions		All respondents (N = 10,109)	Country groups	
			Sweden (N = 2023)	Non-Sweden (N = 8086)
Knowledge[a]*	Knowledge about how home and water is heated	2.87	2.58	2.95
Attention to heat[a]*	Attention paid to the amount of heat used in the home	2.97	2.41	3.11
Satisfaction[b]*	Overall satisfaction with heating and hot water system	3.99	3.85	4.03
Control[a]*	Level of control over current heating and hot water system	2.49	2.17	2.57
Who controls household heating and hot water system[c]**	Myself	7168	966	6202
	My partner	3443	450	2993
	My children	561	70	491
	Other family members	913	125	788
	Guests and visitors	102	19	83
	Maintenance person or technician	1424	734	690
	Others	167	52	115
Temperature[d]*	Home temperature during winter	21.21	21.00	21.26
	Home temperature during summer	19.43	19.17	19.50
	OK to keep heat on all year round	2.04	2.40	1.96

(*continued on next page*)

Table 4 (*continued*)

Questions		All respondents (N = 10,109)	Country groups	
			Sweden (N = 2023)	Non-Sweden (N = 8086)
Common or acceptable heating practices[b]*	OK to keep heat on all day during winter	3.08	4.02	2.87
	Necessary to keep heat on for pets in the home	2.71	3.17	2.60
	Necessary to keep heat on to improve health	3.12	3.46	3.03
	Necessary to keep heat on for the health of the building	3.13	3.70	3.00
	Necessary in winter to occasionally open windows for fresh air	4.11	3.82	4.18
	Necessary to heat every room to maintain a warm household	3.15	3.26	3.13
	Heating is the most important energy service in the home	3.64	3.91	3.57
	Home should be warm enough in winter to wear comfortable clothing indoors (e.g. shorts and t-shirts)	3.01	3.38	2.92
Heating technologies could lead to conflict between[b]*	Housemates	2.66	2.30	2.75
	Couples and partners	2.68	2.37	2.75
	Children and parents	2.63	2.30	2.72
	Landlords and tenants	2.89	2.91	2.88
	Hosts and guests	2.43	2.22	2.49
	Neighbors	2.27	2.16	2.30
Likely to change heating source to another one[b]*	Gas	2.82	2.18	2.96
	Biomass boiler	2.28	2.26	2.29
	Heat pump	2.52	2.87	2.45
	District heating	2.36	2.71	2.28
	Hydrogen	2.14	2.08	2.16
	Oil/fuel oil/LPG	2.02	2.03	2.01
	Solar	2.91	3.02	2.88
	Resistive/electric heating	2.29	2.25	2.30
Current payment type for heating, hot water and cooling services[c]	Pay for the volume of electricity or gas in individual boiler and/or air con system	5293	579	4714
	Pay for the volume of hot water, heat and or cooling use in the home from a centralized system (either in the building or a heat/cooling network)	2156	466	1690
	Pay for the internal temperature level in the home and the building manager takes care of the heating/cooling system	841	324	517
	Don't know	1335	414	921
	Other	484	240	244
Desired benefits of low-carbon heating technologies are[b]*	Save time	3.36	3.14	3.41
	Save money	3.88	3.78	3.91
	Save energy	4.13	4.05	4.14
	Save the environment	4.20	4.08	4.23
	Enhance leisure	3.43	3.44	3.43
	Provide comfort	3.82	3.66	3.86
	Improve security	3.74	3.65	3.76
	Provide care	3.55	3.50	3.57
	Improve quality of life	3.88	3.73	3.91
	Increase property value	3.80	3.77	3.81
	Make life easier	3.77	3.69	3.79
For usability of heating technologies, it is important that they[b]*	Are reliable and easy to use	4.28	4.20	4.30
	Can be controlled and over-ridden	4.12	4.08	4.13
	Protect personal data/information	4.04	3.85	4.08
	Guarantee privacy and confidentiality	4.05	3.84	4.10
	Come with performance warranties	4.23	4.18	4.23
	Are made by credible manufacturers	4.22	4.19	4.23
	Are compatible with other devices in the home	3.93	3.83	3.96
	They are provided with a customized user manual for beginners	4.13	4.08	4.14
Emerging business models[b]*	Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat)	2.72	2.58	2.75
	Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat)	2.70	2.61	2.73
	Warmth payment plan (e.g., charging a house for a set number of warm hours per month)	2.59	2.43	2.63
	Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting)	2.79	2.70	2.81
	Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed …	2.58	2.48	2.61
	Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee)	2.59	2.51	2.61
	Low-carbon heating retrofits	2.84	2.68	2.88
	Community contracts between neighbors (e.g. peer-to-peer energy trading)	2.58	2.58	2.58
Who is trustworthy in heating technologies[b]*	Technology suppliers (e.g. Vaillant or Siemens)	3.72	3.50	3.77
	Heat service providers (e.g., energy service companies)	3.58	3.50	3.60
	Energy suppliers (e.g. EDF or British Gas)	3.59	3.56	3.60
	Government departments (Department for Business, Energy & Industrial Strategy, Federal Ministry for Economic Affairs and Energy)	3.43	3.52	3.41
	Researchers and scientists (universities)	3.65	3.60	3.66
	Friends	3.37	3.25	3.40
	Family	3.48	3.23	3.54
	Neighbors	3.15	3.08	3.16

(*continued on next page*)

Table 4 (*continued*)

Questions		All respondents (N = 10,109)	Country groups	
			Sweden (N = 2023)	Non-Sweden (N = 8086)
	Traditional media (newspapers, TV)	3.06	2.99	3.08
	Social media (Twitter, Facebook, Instagram)	2.73	2.59	2.77
	Tradespersons (builder, plumber, gas fitter)	3.50	3.44	3.52
	Professionals (architects, engineers, technicians, etc.)	3.65	3.58	3.67
	Nobody but myself	3.10	3.01	3.12

Notes.
* Mann Whitney *U* test.
**Chi-Square Color highlight indicates significant at $p < .05$.
[a] Reported as mean values of 4-point Likert type questions (e.g. 1 = Nothing at all to 4 = A lot).
[b] Reported as mean values of 5-point Likert type questions (e.g. 1 = Strongly disagree to 5 = Strongly agree; 1 = Very unlikely to 5 = Very likely; "Don't knows" have been reported as missing values).
[c] Count is frequency to those selecting the answer.
[d] Temperature reported as mean degrees in Celsius.

Interestingly, very cool temperatures (less than 17°) were strongly preferred in the UK (50.2%) compared to all of the other countries in the sample. This could be a slow cultural adjustment to colder homes, due in part to older classes of houses (many built in Victorian times) designed to be heated one room at a time via a fireplace and having poor energy efficiency. This may also reflect class issues embedded in social norms, as for instance the very wealthy upper classes and their houses, as well as the boarding schools they attended, were historically known to be very cold with no central heating [26,29]. While today central heating is common in the UK, many still live in Victorian era houses which are hard to heat. It is the wealthier middle-classes who are more likely for example to retrofit their homes to become more energy efficient [27], whilst many on lower incomes suffer from fuel poverty as a consequent of living in poor energy efficient homes. Many more homes in the UK are in fuel poverty and unable to *afford* warmth than in other countries in our sample, with fuel poverty described as a "national crisis" [28]. It could also be that given more UK homes have boilers they can control, they may manually keep temperatures lower to save gas and thus money (or carbon). The preference for lower temperatures might also be explained by the high relative humidity in general in the UK. In order to feel comfortable with such high humidity, they may believe that temperature must be reduced.

8. Discussion: interconnections, actors and geography

Our survey results not only offer insights by theme or category of the survey, or country location, they also offer insights when analyzed using more robust statistical procedures. Here we focus on three we found particularly interesting: interconnections, actors, and geographic space.

Table 5
British purposes, preferences, and practices of heat compared to all other countries.

Questions		All respondents (N = 10,109)	Country groups	
			UK (N = 2000)	Non-UK (N = 8109)
Knowledge[a]*	Knowledge about how home and water is heated	2.87	2.98	2.85
Attention to heat[a]*	Attention paid to the amount of heat used in the home	2.97	3.13	2.93
Satisfaction[b]*	Overall satisfaction with heating and hot water system	3.99	4.07	3.97
Control[a]*	Level of control over current heating and hot water system	2.49	2.70	2.44
Who controls household heating and hot water system[c]**	Myself	7168	1662	5506
	My partner	3443	711	2732
	My children	561	92	469
	Other family members	913	154	759
	Guests and visitors	102	18	84
	Maintenance person or technician	1424	43	1381
	Others	167	23	144
Temperature[d]*	Home temperature during winter	21.21	20.88	21.29
	Home temperature during summer	19.43	16.56	20.14
Common or acceptable heating practices[b]*	OK to keep heat on all year round	2.04	2.15	2.02
	OK to keep heat on all day during winter	3.08	3.18	3.05
	Necessary to keep heat on for pets in the home	2.71	2.83	2.68
	Necessary to keep heat on to improve health	3.12	3.22	3.09
	Necessary to keep heat on for the health of the building	3.13	3.18	3.12
	Necessary in winter to occasionally open windows for fresh air	4.11	4.03	4.13
	Necessary to heat every room to maintain a warm household	3.15	2.93	3.21
	Heating is the most important energy service in the home	3.64	3.64	3.63
	Home should be warm enough in winter to wear comfortable clothing indoors (e.g. shorts and t-shirts)	3.01	3.09	2.99
Heating technologies could lead to conflict between[b]*	Housemates	2.66	3.06	2.56
	Couples and partners	2.68	3.15	2.56
	Children and parents	2.63	3.02	2.54
	Landlords and tenants	2.89	3.11	2.84
	Hosts and guests	2.43	2.74	2.36

(*continued on next page*)

Table 5 (*continued*)

Questions		All respondents (N = 10,109)	Country groups	
			UK (N = 2000)	Non-UK (N = 8109)
	Neighbors	2.27	2.24	2.28
Likely to change heating source to another one[b]*	Gas	2.82	2.94	2.79
	Biomass boiler	2.28	2.13	2.32
	Heat pump	2.52	2.22	2.60
	District heating	2.36	2.09	2.43
	Hydrogen	2.14	2.04	2.17
	Oil/fuel oil/LPG	2.02	1.90	2.04
	Solar	2.91	2.54	3.00
	Resistive/electric heating	2.29	2.15	2.33
Current payment type for heating, hot water and cooling services[c]	Pay for the volume of electricity or gas in individual boiler and/or air con system	5293	1237	4056
	Pay for the volume of hot water, heat and or cooling use in the home from a centralized system (either in the building or a heat/cooling network)	2156	299	1857
	Pay for the internal temperature level in the home and the building manager takes care of the heating/cooling system	841	51	790
	Don't know	1335	359	976
	Other	484	54	430
Desired benefits of low-carbon heating technologies are[b]*	Save time	3.36	3.33	3.36
	Save money	3.88	3.80	3.90
	Save energy	4.13	4.15	4.12
	Save the environment	4.20	4.22	4.20
	Enhance leisure	3.43	3.29	3.47
	Provide comfort	3.82	3.81	3.82
	Improve security	3.74	3.27	3.85
	Provide care	3.55	3.44	3.58
	Improve quality of life	3.88	3.73	3.91
	Increase property value	3.80	3.66	3.84
	Make life easier	3.77	3.66	3.80
For usability of heating technologies, it is important that they[b]*	Are reliable and easy to use	4.28	4.30	4.27
	Can be controlled and over-ridden	4.12	4.18	4.11
	Protect personal data/information	4.04	4.11	4.02
	Guarantee privacy and confidentiality	4.05	4.10	4.04
	Come with performance warranties	4.23	4.22	4.23
	Are made by credible manufacturers	4.22	4.22	4.22
	Are compatible with other devices in the home	3.93	3.99	3.92
	They are provided with a customized user manual for beginners	4.13	4.15	4.12
Emerging business models[b]*	Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat)	2.72	2.50	2.77
	Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat)	2.70	2.51	2.74
	Warmth payment plan (e.g., charging a house for a set number of warm hours per month)	2.59	2.44	2.62
	Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting)	2.79	2.69	2.81
	Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed …	2.58	2.42	2.62
	Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee)	2.59	2.46	2.62
	Low-carbon heating retrofits	2.84	2.73	2.87
	Community contracts between neighbors (e.g. peer-to-peer energy trading)	2.58	2.40	2.62
Who is trustworthy in heating technologies[b]*	Technology suppliers (e.g. Vaillant or Siemens)	3.72	3.68	3.74
	Heat service providers (e.g., energy service companies)	3.58	3.48	3.60
	Energy suppliers (e.g. EDF or British Gas)	3.59	3.48	3.62
	Government departments (Department for Business, Energy & Industrial Strategy, Federal Ministry for Economic Affairs and Energy)	3.43	3.35	3.45
	Researchers and scientists (universities)	3.65	3.66	3.65
	Friends	3.37	3.56	3.33
	Family	3.48	3.68	3.43
	Neighbors	3.15	3.25	3.12
	Traditional media (newspapers, TV)	3.06	3.05	3.06
	Social media (Twitter, Facebook, Instagram)	2.73	2.70	2.74
	Tradespersons (builder, plumber, gas fitter)	3.50	3.51	3.50
	Professionals (architects, engineers, technicians, etc.)	3.65	3.63	3.66
	Nobody but myself	3.10	3.30	3.05

Notes.

* Mann Whitney *U* test.

**Chi-Square Color highlight indicates significant at $p < .05$.

[a] Reported as mean values of 4-point Likert type questions (e.g. 1 = Nothing at all to 4 = A lot).

[b] Reported as mean values of 5-point Likert type questions (e.g. 1 = Strongly disagree to 5 = Strongly agree; 1 = Very unlikely to 5 = Very likely; "Don't knoww" have been reported as missing values).

[c] Count is frequency to those selecting the answer.

[d] Temperature reported as mean degrees in Celsius.

8.1. Interconnections

When examined through more sophisticated multivariate analysis (to complement our univariate and bivariate analysis above), we do see some compelling interconnections and intersections among the different aspects of our survey as well as demographic attributes.

In Table 6, we observe a positive significant correlation of household income with the habit of keeping the heating system operating the whole day. However, as expected, a higher income also correlates with the willingness to pay more to switch to low carbon energy sources, associated to a better awareness and engagement towards energy saving and pro-environment behaviors.

Surprisingly, we see that energy literacy is not correlated with the intention to change the energy source to solar. This may pave the way toward a much needed awareness campaign, focused on solar energy, developed for a general audience, of different cultural and education backgrounds.

It seems that younger people, and those with more children at home, are those more willing to change. Therefore, a possible positive trend could be observed in the short future.

Results also show that literacy increases with age and is higher for males than for women.

The low-attention attitude of wearing T-shirts and shorts at home all year around is, unfortunately as expected, associated to the practice of keeping the heating on the whole day. This practice is for example common in Sweden, as shown by 45.3% of respondents.

8.2. Actors, households and poverty

We also examined our results through the lens of actors, or at least how different types of households—those owned, rented, in social housing, and so on—may have meaningful differences across the survey

Table 6
Pearson coefficients for heating practices, preferences, and demographic attributes across five European countries (N = 10,109).

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Literacy	1												
2	Heating All Day	-.063**	1											
3	Winter T-Shirts	-.068**	.340**	1										
4	Temperature Winter	−0.017	.080**	.150**	1									
5	Temperature Summer	.076**	-.049**	-.095**	.269**	1								
6	Pay Extra Low Carbon	0.003	.054**	.022*	-.024*	−0.013	1							
7	Change To Solar	−0.019	.072**	.055**	−0.017	-.040**	-.043**	1						
8	People At Home	.024*	-.043**	.031**	.043**	−0.016	.062**	-.095**	1					
9	Children	0.019	.024*	.079**	.044**	-.026**	.106**	-.111**	.548**	1				
10	Education	.067**	−0.002	0.004	0.015	.037**	−0.001	0.002	0.005	.047**	1			
11	Age	.188**	0.013	-.094**	-.025*	.105**	−0.016	.121**	-.257**	-.271**	0.010	1		
12	Gender Male	.192**	0.014	.081**	−0.002	.062**	.021*	0.019	-.028**	-.061**	.037**	.181**	1	
13	Household Income	-.044**	.247**	.092**	−0.001	.026**	.188**	-.037**	−0.003	.066**	0.000	.059**	.044**	1

*p < .05; **p < .01.
Source: authors

Table 7
Examining the actor preferences of low-carbon heating responses across five European countries with Welch tests.

Variable	Statistic	Sig.	Mean	Games-Howell Post-hoc Analysis			
				Mortgage	Owned	Rented	Social Housing
Literacy	184.35	.000	Mortgage = 2.92		***	***	***
			Owned = 3.06	***		***	***
			Rented = 2.66	***	***		***
			Social Housing = 2.50	***	***	***	
Heating all Day	51.30	.000	Mortgage = 3.18		***		***
			Owned = 2.91	***		***	***
			Rented = 3.10		***		***
			Social Housing = 3.49	***	***	***	
Winter T-Shirts	38.93	.000	Mortgage = 3.07		***		***
			Owned = 2.88	***		***	***
			Rented = 3.04		***		***
			Social Housing = 3.34	***	***	***	
Temperature Winter	1.35	.256	Mortgage = 21.13				
			Owned = 21.19				
			Rented = 21.24				
			Social Housing = 21.42				
Temperature Summer	34.16	.000	Mortgage = 19.33		***		***
			Owned = 19.90	***		***	***
			Rented = 19.26		***		***
			Social Housing = 18.12	***	***	***	
Pay Extra Low Carbon	11.91	.000	Mortgage = 1015.57		***	***	***
			Owned = 277.06	***			
			Rented = 192.01	***			
			Social Housing = 209.31	***			
Change to Solar	8.56	.000	Mortgage = 2.96		***	**	*
			Owned = 3.14	***			
			Rented = 3.11	**			
			Social Housing = 3.15	*			

*p < .05; **p < .01; ***p < .001.

evidence. As group variances were not homogeneous, we used the Welch test in lieu of the classical One-way ANOVA and carried out the Games-Howell post hoc analysis [12]. Welch tests are significant for all the selected variables, with p values always less than 0.001. These findings highlight the role played by the country of respondents in affecting energy-related behaviors, probably due to a variety of local differences (social, cultural, economic and regulatory aspects; climate conditions, etc.). In Table 7, we group survey observations by property ownership – to see if literacy, willingness to change and behaviors were significantly different while comparing house owners, tenants, people living in social houses and those paying a mortgage. In this way, we carried out a variance analysis considering an economic variable, to evaluate its impact on energy-related behaviors and attitudes.

As Table 7 indicates, almost all Welch tests are significant, excluding that of temperature in winter, which looks like a very "individual" attitude. Respondents who pay a mortgage and house-owners are more willing to pay extra fees for a low-carbon energy system, since they probably have a long-term vision, are concerned and care about the environment. As expected, they showed a better literacy with respect to the topic. This may be motivated by their general higher willingness to invest and ask for credit, or by their better economic condition, since they may have access to credit through their mortgage, for instance.

By contrast, respondents living in social housing – and, most probably, not charged for energy fees or maintenance costs – act less responsibly, for example by keeping the heating on the whole day or by wearing light clothes even in winter. This is also partially true for tenants because they are typically less aware of the specificity of energy bills and paying fix maintenance costs does not provide a clear understanding about energy consumption. In addition, people living in social houses seem to pay less attention to summer cooling setpoints, while no significant differences are observed about heating temperatures in winter.

Willingness to switch to solar energy as a thermal vector are in general high, with a relatively minor difference among the categories, except for the respondents paying a mortgage and those of the other categories.

8.3. Geography and space

Lastly, intersectional preferences and findings emerge via a geographic and spatial lens as well. For instance, the belief about wearing summer clothing in the winter was the strongest in our two northernmost countries of Sweden (45.3%) and the UK (38.6%), even though these countries have the coldest climates (and thus one may expect greater heat awareness or more reasonable expectations). The cold season may merely be too long in the minds of respondents to wait for summer to wear shorts and T-shirts. Furthermore, almost half (46.9%) of Swedish respondents, and roughly one-third of Italian (37%), Spanish (35%), and German (31%) respondents also indicated they would pay more than €20/month for low-carbon heat. The UK and Sweden may need constant heat in the winter months, unless occupants live in a passive house, and different than the milder winters in Germany, Italy and Spain.

Table 8 shows the analysis of variance we carried out to see if significant differences in mean literacy, willingness to change and energy-related behaviors could be imputable to the country of respondents. As expected through the survey observation, a large difference is found out for the temperature setup, with a more significant ANOVA for the summer temperature than for the winter one.

To investigate this further, in Table 9, we reported the interaclass

Table 8
Examining geographical and spatial differences in low-carbon heating responses across five European countries with Welch tests.

Variable	Statistic	Sig.	Mean	Games-Howell Post-hoc Analysis				
				Germany	Italy	Spain	Sweden	UK
Literacy	137.14	.000	Germany = 2.77		***	***	***	***
			Italy = 3.14	***		***	***	***
			Spain = 2.90	***	***		***	*
			Sweden = 2.58	***	***	***		***
			UK = 2.89	***	***	*	***	
Heating all Day	628.20	.000	Germany = 3.51		***	***	***	***
			Italy = 2.36	***			***	***
			Spain = 2.42	***			***	***
			Sweden = 4.02	***	***	***		***
			UK = 3.18	***	***	***	***	
Winter T-Shirts	73.50	.000	Germany = 3.00		***	*	***	
			Italy = 2.73	***		***	***	***
			Spain = 2.87	*	***		***	***
			Sweden = 3.38	***	***	***		***
			UK = 3.09		***	***	***	
Temperature Winter	24.14	.000	Germany = 21.28			***	*	*
			Italy = 21.03			***		
			Spain = 21.83	***	***		***	***
			Sweden = 21.00	*		***		
			UK = 20.88	*		***		
Temperature Summer	204.10	.000	Germany = 19.78		***	***	***	***
			Italy = 20.73	***			***	***
			Spain = 20.87	***			***	***
			Sweden = 19.17	***	***	***		***
			UK = 16.56	***	***	***	***	
Pay Extra Low Carbon	21.38	.000	Germany = 60.78				***	
			Italy = 88.19				***	
			Spain = 151.66				***	
			Sweden = 1785.27	***	***	***		***
			UK = 93.77				***	
Change to Solar	84.88	.000	Germany = 3.35		***	***	***	
			Italy = 2.72	***		***	***	***
			Spain = 2.97	***	***			***
			Sweden = 2.98	***	***			***
			UK = 3.09		***	***	***	

*p < .05; **p < .01; ***p < .001.

Table 9
Intraclass correlation coefficients for selected heating practices by country

Variable	ICC
Literacy	4.90%
Heat All Day	20.15%
Winter T-Shirts	2.91%
Temperature Winter	0.84%
Temperature Summer	9.53%
Pay Extra Low Carbon	2.48%
Change To Solar	3.60%

correlation coefficients calculated for empty multilevel regression models with fixed effects [13,14], with observations grouped by country. These indicate the proportion of variance explained by the grouping structure, for each variable. As the table shows, the habit of keeping the heating on all day has 20% of variance at the country level, whereas all the other variables exhibit a smaller proportion of variance that depends on the country.

9. Conclusion

The influence of demographics and geography on decarbonizing household heat—rooted in stated knowledge and literacy of heating, heating practices and dynamics, temperature preferences, priorities and willingness to change, and country variation—is important and complex. In terms of knowledge and literacy, a majority of our respondents across the five countries report relying exclusively on fossil fuels (especially gas) for their heat, and many homes reported using this gas inefficiently, that is almost 90% stated they have limited to no heating controls at all. Qualitative statements from respondents also strongly suggest that as important as heating control is, it is difficult for them to understand and many reported misusing heating.

In terms of sustainability, a surprising number of households reported that it was important and acceptable to them to heat their homes all year round, even in the summer, and almost three-quarters of respondents in UK, Italy, and Germany admitted to opening windows in the middle of winter to let in fresh air (but letting heat out). Other very common practices included heating every room, even those that are unoccupied; overheating for pets; and overheating to wear summer clothing in the winter. Some respondents even seriously discussed heating to turn their bum red, to heat socks, and to give their boilers fond names such as "Baby." Our evidence reveals also that heating practices can not only empower households with warmth, but culminate in conflict, with possible tensions with landlords but also other family members, guests, and even neighbors.

In terms of temperature settings, our respondents reported demanding a huge range of temperatures which also fluctuate widely across households and winter and summer seasons. While roughly 60% of respondents reported a narrower range of preferred heat temperature between 20 and 22° in the winter, another 40% reported preferences far outside this range, some as high as 30, others as low as 2. Moreover, most respondents (more than half) reported being satisfied to very satisfied with their existing heating systems, perhaps creating a tractable barrier to change. That said, others reported deficient and defunct heating systems that were so bad they literally started fires, or heating so unreliable people had to cope by sitting in heated cars in the winter or stockpiling extra boilers around the house.

In terms of desirability of change, some respondents (about one-third) stated they would prefer switching to solar and slightly less to natural gas, but other options such as hydrogen or electric heat were poorly rated and ranked. And, while respondents reported a large range in their willingness to pay for low-carbon heat, these findings were inconsistent and unreliable, ranging from €0 (a very common answer) to €99,999 per month (perhaps indicating low-carbon solutions have perceived infinite value). If households were going to adopt low-carbon heat, the survey suggests that reliability and ease of use in particular are the highest preferred. Whatever engineers or designers do to make heating systems "smarter" should first and foremost be concerned with making them easy to use and reliable. Adding to the complexity of the systems as a matter of making them "smarter" is against the highest preference of the energy users who want more reliable and easy to use systems. Respondents lastly reported being not very well informed or supportive about emerging business models such as heat as a service or P2P trading; none of these were strongly supported or supported by more than about a quarter of respondents. The most trustworthy entities identified by the survey were not traditional media, friends, or scientists, but perhaps oddly technology suppliers and professional technicians.

In terms of country variation, our evidence suggests that the Germans are far more likely than others to heat all year round. Italians express a preference more than others for heating every room, whereas Spanish respondents report prioritizing monetary savings. Swedish households are more likely to overheat their homes for pets, and British households report much cooler temperatures than other countries. These elements underscore perhaps the cultural elements of heat.

Our findings suggest that the decisions made about heating, space cooling, and hot water are not always purposively rational. Ongoing actions, preferences, and practices about household heat are seamlessly interconnected with technologies but also demographic attributes, complex goals, myopic preferences and a host of unsustainable behaviors. The decisions made about heat far extend beyond solely economic self-interest, logic, rationality or even a desire to save the planet and reduce emissions. Some households seem to care very much about their heat, are knowledgeable about its sources, strongly adamant in their preferences, and firm in their temperature settings. Others seem to care less, to even put heat to use to play practical jokes (making roommates sweat in the summer, inducing cold water while someone is showering), or they have very low self-reported literature or a wide and waffling array of temperature preferences.

This great variety of heating literacy, practices, preferences and priorities offers a very strong critique towards attempts to push the sector towards decarbonisation by applying "one-size-fits-all" policy options, e.g. a carbon tax, or a particular technology, e.g. a heat pump or a boiler, which would be unlikely to satisfy all stated preferences within our survey at all stated times and seasons. This complexity suggests that the decarbonisation of household heat is a co-evolutionary and dynamic process that transcends markets and infrastructures—being both shaped by them but also shaping their diffusion. Our survey results show how household literacy (or lack of it), experience, trust and wasteful practices may be just as important to many households as design of a heating system technology or how many tons of carbon it may displace. Policy and research must come to accept this myopia if it is ever to make further progress at decarbonizing the European heating sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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